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Final Report

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16. Abstract This report contains a summary of available fire suppression agents and their properties. The applicability of various technologies for each major onboard aircraft application is assessed. Classes of agents, with presently available agents listed, are recommended for use in the development of test protocols. The test protocol developed for a class of agents can be used, with minor modifications, to test all agents belonging to that class.					
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PREFACE

The United States Federal Aviation Administration (FAA) is conducting a program to determine performance criteria and certification methods with the objective of developing Minimum Performance Standards (MPSs) for nonhalon fire extinguishing and suppression systems onboard aircraft. This program is being performed in cooperation with the Joint Aviation Authorities (JAA) in Europe, the Civil Aviation Authority (CAA) in the United Kingdom, and Transport Canada Aviation (TCA). The International Halon Replacement Working Group (IHRWG) was established by the FAA and cooperating agencies to provide input for this program. Participants include aviation regulatory authorities, other government agencies involved in research and development, airframe manufacturers, airlines, industry associations, manufacturers and suppliers of fire protection equipment and agents, and researchers.

The first meeting of the IHRWG was held on 13-14 October 1993 at the FAA Technical Center, Atlantic City International Airport, New Jersey, USA. A number of task groups were established at that meeting. Among these were task groups for the four onboard areas of aircraft fire protection: cargo compartment, engine nacelle, passenger cabin (hand helds), and lavatory. Task Group 6, now designated as the Task Group on Halon Options, was assigned to review chemical options to halons. A major goal for this Task Group was to recommend two to three agents for use in developing FAA test protocols for each major area of onboard aircraft use: (1) engine nacelles, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection. The final report of Task Group 6 was published in February 1995, Chemical Options to Halons for Aircraft Use, DOT/FAA/CT-95/9.

At the 19-20 April 1995 meeting of the IHRWG in Rome, Italy, a decision was made to maintain a review of new halon option technologies as they appeared and to continue to update the February 1995 report. All members of the original Task Group were contacted to determine who wished to maintain membership, and an announcement was made to find new members. This group prepared a second updated report, Halon Replacement Options for Use in Aircraft Fire Suppression Systems, DOT/FAA/AR-96/90, September 1996.

At an IHRWG meeting in London on 9-10 October 1996, a decision was made to continue the work of the Task Group on Halon Options and to begin preparation of a second update of the initial February 1995 report. This report is that update. A slight change in the mandate was issued to assess the applicability of various technologies for each major onboard aircraft application rather than to recommend agents for development of test protocols. The major areas of onboard aircraft use are (1) engine nacelles and APU (auxiliary power unit), (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection.

The focus of the IHRWG has recently been expanded to include all system fire protection research and development for aircraft. The name of the working group was changed to the International Aircraft Systems Fire Protection Working Group.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AEL	Acceptable Exposure Limit
AIHA	American Industrial Hygiene Association
ALC	Approximate Lethal Concentration
APU	auxiliary power unit
CAA	chemical action agent
CAA	Civil Aviation Authority
CFC	chlorofluorocarbon
CNS	central nervous system
DARPA	Defense Advanced Research Projects Agency
DNA	deoxyribonucleic acid
DoD	Department of Defense
EC	European Community
ECG	electrocardiographic
EGL	Emergency Guidance Level
EMAA	Encapsulated Micron Aerosol Agent
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guideline
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FC	(per)fluorocarbon
FIC	fluoroiodocarbon
FMRC	Factory Mutual Research Corporation
GWP	Global Warming Potential
HAG	Halon Alternatives Group
HARC	Halon Alternatives Research Corporation
HBFC	hydrobromofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HMIS	Hazardous Materials Identification System
HTOC	Halon Technical Options Committee
IDLH	Immediately Dangerous to Life and Health
IPCC	Intergovernmental Panel on Climate Change
IHRWG	International Halon Replacement Working Group
JAA	Joint Aviation Authorities
LEL	Low Effect Level
LOAEL	Lowest Observed Adverse Effect Level
MPS	Minimum Performance Standard
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NEAG	New Extinguishants Advisory Group
NEL	No Effect Level
NIOSH	National Institute for Occupational Safety and Health

NIST	National Institute of Standards and Technology
NMERI	New Mexico Engineering Research Institute
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No Observed Adverse Effect Level
NPCA	National Paint and Coatings Association
ODP	Ozone Depletion Potential
OSHA	Occupational Safety and Health Administration
PAA	physical action agent
PBPK	physiologically based pharmacokinetic modeling
PEL	Permissible Exposure Limit
PFC	perfluorocarbon
PGA	pyrotechnically generated aerosol
PVC	polyvinyl chloride
REL	Recommended Exposure Limit
RPU	Rotor Positioning Unit
SCBA	self-contained breathing apparatus
SNAP	Significant New Alternatives Policy
SPGG	solid propellant gas generator
STEL	Short-Term Exposure Limit
TCA	Transport Canada Aviation
TLV	Threshold Limit Value
TOGW	takeoff gross weight
TWA	Time Weighted Average
UDS	unscheduled DNA synthesis
UL	Underwriters Laboratories
UNEP	United Nations Environment Programme
U.S.	United States
WEEL	Workplace Environmental Exposure Limit
WGL	Workplace Guidance Level

EXECUTIVE SUMMARY

This report which is an update of two earlier reports published in February 1995 and September 1996 [1, 2], summarizes available fire suppression technologies that could be considered as halon substitutes for the four major aircraft onboard applications: (1) engine nacelles, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection. The options are divided into two groups: replacements (halocarbon agents) and alternatives (all other options). The technologies are discussed and the applicability of each is assessed for the four primary applications.

During preparation of this report, draft versions were updated and posted on an Internet site to permit review, comment, and recommendations by the International Halon Replacement Working Group members and others. In particular, manufacturers were informed of the Internet posting to allow review and comment on discussions of their products.

1. INTRODUCTION.

1.1 OVERVIEW OF FIRE PROTECTION.

The most common fuels in fire and explosion incidents are petroleum products, cellulosic materials (wood, paper), and polymers. Fires of cellulosic materials are termed "Class A" and liquid fuel fires are termed "Class B." Polymeric material fires can exhibit characteristics of either Class A or Class B depending on the extent of melting (if any) during combustion. Class C fires involve energized electrical equipment and Class D fires, flammable metals. Rapid gas phase combustion can result in an explosion or, in the limit as the combustion becomes very rapid, detonation.

There are five general types of fire and explosion protection applications for aircraft: (1) total-flood fire extinguishment, (2) total-flood fire suppression (3) streaming fire extinguishment, (4) explosion suppression, and (5) inertion against explosions and fires. The Fire Protection Handbook and the SFPE Handbook of Fire Protection Engineering are excellent sources of information on all aspects of fire and explosion protection [3 and 4].

In total-flood applications, an extinguishing agent is discharged into an enclosed space to achieve a concentration sufficient to extinguish or suppress an existing fire. The agent concentration that a system/agent combination is designed to produce is termed the "design concentration." Total-flood extinguishment usually uses fixed systems (e.g., nonportable systems attached to a protected structure) with either manual or automatic activation. Automatic systems detect a fire and automatically discharge the extinguishing agent. Total-flood applications include protection of enclosed spaces such as aircraft cargo compartments.

In streaming applications, an agent is applied directly onto a fire or into the region of a fire. This is usually accomplished using manually operated wheeled or portable extinguishers. Hand-held portable extinguishers provide fire protection in aircraft passenger compartments.

Halons are bromine-containing gaseous or volatile liquid chemicals used in fire and explosion protection. Most widely employed are Halon 1301, bromotrifluoromethane (CBrF_3), used primarily as a total-flood agent, and Halon 1211, bromochlorodifluoromethane (CBrClF_2), used primarily in streaming applications. These clean (residue-free) chemicals are applicable to Class A, B, and C fires. They cannot be used for Class D fires.

1.2 ENVIRONMENTAL OVERVIEW.

Although airworthiness regulations do not require the use of a particular fire suppression agent, halons have been the agents of choice of airframe manufacturers. For all practical purposes, production of halons has ceased under the provisions of the Montreal Protocol. The primary environmental characteristics to be considered in assessing a new chemical option to halons are Ozone Depletion Potential (ODP), Global Warming Potential (GWP), and Atmospheric Lifetime. The agent selected should have environmental characteristics in harmony with international laws and agreements, as well as applicable national, state, and local laws. An agent that does not have a zero or near-zero ODP and the lowest practical GWP and Atmospheric Lifetime may have problems of international availability and commercial longevity.

1.3 TOXICOLOGY OVERVIEW.

The toxicological acceptability of a chemical option to halons is dependent on its use pattern. As a general rule, the agent must not pose an unacceptable health risk for workers during installation, maintenance, or operation of the extinguishing system. In areas where passengers or workers are present, or where leakage could cause the agent to enter the passenger compartment, at no time should the cumulative toxicological effect of the agent, its pyrolytic breakdown products, and the byproducts of combustion pose an unacceptable health risk during probable normal and failure conditions.

1.4 OPTIONS.

The following defines some terms used in this report. The term "options" is used for anything that could be used in place of halons. "Replacements" denote halocarbon fire extinguishants, i.e., agents that are chemically similar to the present halons. "Alternatives" are everything else.

"Chemical alternatives" are materials such as carbon dioxide (CO₂), foam, water, and dry chemicals, whose chemistry differs significantly from that of the halons. "Engineering alternatives" (not covered in this report) involve such approaches as rapid response and fire-resistant structures. Note that many alternative technologies are actually "chemical/system" alternatives since the agent and system cannot be separated (e.g., solid propellant gas generators, SPGGs).

Alternatives and replacements have been discussed in a number of papers (recent overviews are given in references 5 and 6).

Any option to the use of halons must have U.S. Environmental Protection Agency (EPA) approval under the Significant New Alternatives Policy (SNAP) program, which implements section 612 of the amended Clean Air Act of 1990. Following publication of an advance notice of proposed rule making and a request for data on new chemicals [7], the EPA published the proposed plan for the SNAP program and an initial proposed list of decisions on acceptable and unacceptable halon substitutes on 12 May 1993 [8]. The final plan and the first list were promulgated on 18 March 1994 [9]. This initial list was prepared from an EPA background document for halon replacements and alternatives [10]. A current list of acceptability decisions can be found on the EPA website [11 and 12]. Substances prohibited, acceptable only under certain conditions or for certain uses, or removed from a list of prohibited or acceptable substitutes are subject to public comment. Other substances for which there are no limitations are listed as acceptable with no public comment required.

2. HALOCARBON REPLACEMENTS.

At present, halon replacements (e.g., halocarbons) fall into four major categories (see table 1). Note that two categories noted in the first report from the Task Group on Chemical Options to Halons [1]—CFCs (chlorofluorocarbons) and HBFCs (hydrobromofluorocarbons)—are no longer being commercialized.

TABLE 1. CLASSES OF HALON REPLACEMENTS

HCFCs	Hydrochlorofluorocarbons
FCs (PFCs)	Perfluorocarbons
HFCs	Hydrofluorocarbons
FICs	Fluoroiodocarbons

There are a number of desirable characteristics for replacement agents. They must have acceptable global environmental characteristics (low ODPs, low GWPs, and low atmospheric lifetime) and an acceptable toxicity. A continuing debate on acceptable levels for these characteristics is expected. The primary reason for using halocarbons, rather than such alternatives as foams and dry chemicals, is that halocarbons are clean, volatile, and electrically nonconductive. Finally, the agent must be effective. Note, however, that effectiveness does not necessarily mean as effective as the present halons, though this is desirable.

Physical action agents (PAAs) are those that operate primarily by heat absorption. Chemical action agents (CAAs) are those that operate primarily by chemical means — removal of flame-free radicals. The chemical effect contribution to extinguishment by PAAs is only 10 to 25 percent of the physical contribution [13]. In general, CAAs are much more effective extinguishants than are PAAs. Halons 1211 and 1301 are primarily CAAs. Work at the Naval Research Laboratory (NRL) indicates that Halon 1301 extinguishment of n-heptane in air is approximately 20 percent physical and 80 percent chemical [14]. The analysis also indicates that about 25 percent of the extinguishment is due to the CF_3 group and about 55 percent is due to the bromine. Though CAAs are more effective, they often have higher ODPs because they often contain bromine. One exception is trifluoroiodomethane, CF_3I [15], which is the only CAA being commercialized today.

Most halocarbons now proposed as halon replacements require significantly higher concentrations than required for Halons 1301 and 1211 and produce larger amounts of toxic or corrosive byproducts (e.g., hydrogen fluoride and, for chlorine-containing agents, hydrogen chloride) [16]. One halocarbon, CF_3I , produces relatively large amounts of iodine. Byproduct formation is strongly influenced by the mass flux of inhibitor into the flame sheet and the extinguishment time. Slow extinguishment due to the use of lower concentrations of agent produces more byproducts.

2.1 TOXICOLOGY.

2.1.1 Acute Toxicological Indices.

Table 2 contains a summary of acute toxicological indices. These are discussed in more detail in the following text.

2.1.1.1 Lethality.

The LC_{50} is defined as the concentration of a chemical that causes death in 50 percent of animals exposed for a specified duration of time. The test animals are observed during exposure and for

a period of 14 days following exposure for lethality. The approximate lethal concentration (ALC) value, first established by DuPont but now used by other chemical manufacturers, approximates the lowest concentration that causes death (LC_{LO}). Thus, it is lower than the LC_{50} value. The ALC value is often used in place of the LC_{50} in assessing safety.

TABLE 2. ACUTE TOXICOLOGICAL INDICES

Exposure Limit		Definition
ALC	Approximate Lethal Concentration	The approximate concentration considered to cause death, similar to LC_{LO} but often used in place of LC_{50} when making assessments.
LC_{50}	Lethal Concentration—50%	Concentration causing death in 50% of an animal test population exposed for a specified duration of time.
LC_{LO}	Lethal Concentration—Low	The lowest observed lethal concentration
AD_{50}	Anesthetic Dose—50%	Dose causing anesthesia in 50% of an animal test population.
RD_{50}	Respiratory Dose—50%	Dose causing a 50% decrease in respiratory rate.
LOAEL	Lowest Observed Adverse Effect Level	The lowest exposure level that has been observed to cause an adverse effect. For inhalation of halocarbons, the effect is usually cardiac sensitization.
NOAEL	No Observed Adverse Effect Level	The highest exposure level that has been observed to cause no adverse effect. For inhalation of halocarbons, the effect looked for is usually cardiac sensitization.

2.1.1.2 Irritation.

The RD_{50} , the dose that causes a 50 percent decrease in respiratory rate, has been proposed as a measure of irritation of nasal mucosa [17]. The RD_{50} response in animals appears to correspond to eye, nose, and throat irritation in humans.

2.1.1.3 Anesthesia.

Anesthesia is the condition of loss of consciousness, usually coupled with the loss of response to pain and other stimuli. General anesthesia results from a depression of the central nervous system (CNS) and can be exerted by a wide range of chemicals. Some anesthetic agents elicit CNS depression through specific receptor sites; whereas others have more generalized actions on other cellular sites such as the cell membrane. Anesthetic potency of chemicals is tested in experimental animals by observing decrements in coordination, loss of righting reflex (inability to stand upright after being placed on the back), reduced alerting response to an auditory stimulus, etc. The AD_{50} is the calculated value corresponding to the concentration at which 50 percent of the test animals experience anesthesia. Anesthetic potency or mild CNS depression can also be observed in humans using performance decrement studies.

2.1.1.4 Cardiac Sensitization.

Cardiac sensitization is the term used for the phenomenon of the sudden onset of cardiac arrhythmias caused by a sensitization of the heart to epinephrine (adrenaline) in the presence of some concentration of a chemical. Cardiac sensitization (specifically leading to ventricular fibrillation) was first demonstrated in 1912 in cats exposed to chloroform in the presence of epinephrine, which was nonhazardous without epinephrine [18]. Since then, cardiac sensitization has been demonstrated in humans as well as laboratory animals.

When comparing concentrations necessary to elicit acute toxic responses such as anesthesia, cardiac sensitization, or lethality, cardiac sensitization usually occurs at a lower concentration for halocarbons than other acute toxicity endpoints. Therefore, regulatory and standard-making authorities have used cardiac sensitization thresholds as the criterion for determining acceptability for use in areas where human occupancy may occur. Cardiac sensitization is particularly important in firefighting. Higher levels of epinephrine secreted by the body, under the physiological stress of a fire event, may increase the possibility of sensitization.

The experimental procedure used to investigate the cardiac sensitization potential of a chemical involves outfitting dogs with electrocardiographic (ECG) measurement devices and exposing the animals to a sequence of agent and epinephrine [19]. Healthy male beagle dogs (generally six or more animals per exposure concentration), between 1 and 2 years old, are trained to stand in a cloth sling and to wear a snout mask. The dogs also learn to accept venipuncture and ECG monitoring. Thus, they are minimally stressed during the experiment.

The usual sequence of exposure is that the animal is monitored in a baseline condition without any intervention for 2 minutes (see table 3). Epinephrine is then intravenously infused to determine the effect of this catecholamine on the cardiac system. The dose and time period for infusion varies slightly between laboratories; however, the levels of epinephrine given are always in the pharmacological rather than the physiological range. (A pharmacological dose is considered to be greater than any potential innate physiological dose.) After approximately 5 minutes from the initial epinephrine administration, the agent is given as a continuous inhalation exposure either through a mask fitting over the dog's snout or in an exposure chamber. After a 5-minute agent exposure, epinephrine is administered intravenously (epinephrine challenge) along with the continuous agent exposure. The animals are monitored for another 5 minutes to determine the effect of epinephrine and agent. This protocol is performed at increasingly higher doses until a marked adverse response occurs.

TABLE 3. PROTOCOL FOR TESTING CARDIAC SENSITIZATION IN DOGS

Time, minutes	Procedure
0	Start ECG recording
2	Administer epinephrine dose
7	Start inhalation of test gas or air
12	Administer epinephrine challenge dose
17	Stop test gas inhalation; stop ECG recording

A marked adverse response is one considered, in the judgment of the toxicologist, as the appearance of five or more multifocal ventricular ectopic beats or ventricular fibrillation that may be fatal [20]. A mild response is described as an increase in the number of isolated abnormal beats (less than five consecutive beats) following the epinephrine challenge (second epinephrine administration). The threshold level is the lowest concentration at which cardiac sensitization occurs. No definitive rule exists indicating the number of animals that must experience a marked response to determine the threshold value. In most cases, even one animal experiencing a marked response constitutes establishment of a threshold value. This level is also called the Lowest Observed Adverse Effect Level (LOAEL). The highest concentration at which no marked responses occur is called the No Observed Adverse Effect Level (NOAEL). For halocarbons, these values are used when determining safe exposure levels for humans. While it is not known with certainty whether the LOAEL and NOAEL in dogs accurately represent these values in humans, the dog is the preferred animal model for determining cardiac physiology.

LOAEL and NOAEL concentrations entail measurement of cardiotoxic effects in animals made sensitive to these effects by the administration of epinephrine. The administered epinephrine doses are just below the concentration at which epinephrine alone would cause cardiotoxicity in the experimental animal and are approximately ten times greater than the concentration a human would be likely to secrete under stress. Thus, LOAEL and NOAEL values are conservative even in high-stress situations [10].

Because the cardiac sensitization potential is measured in dogs, a means of providing human relevance to the concentration at which this cardiosensitization occurs (LOAEL) has been established through the use of physiologically based pharmacokinetic (PBPK) modeling.

The PBPK model, as described in the National Fire Protection Association (NFPA) 2001 standard, provides safe human exposure times for various concentrations of halocarbons [21]. A PBPK model is a computerized tool that describes time-related aspects of a chemical's distribution in a biological system. The PBPK model mathematically describes the halocarbon uptake into the body and the subsequent distribution of the halocarbon to the areas of the body where adverse effects can occur. For example, the model describes the breathing rate and uptake of the halocarbon from the exposure atmosphere into the lungs. From there, the model uses the blood flow bathing the lungs to describe the movement of the halocarbon from the lung space into the arterial blood that directly feeds the heart and vital organs of the body.

It is the ability of the model to describe the halocarbon concentration in human arterial blood that provides its primary utility in relating the dog cardiac sensitization test results to a human who is unintentionally exposed to the halocarbon. The concentration of the halocarbon in the dog arterial blood at the time the cardiac sensitization occurs (5-minute exposure) is the critical arterial blood concentration, and this blood parameter is the link to the human system. Once this critical arterial blood concentration has been measured in dogs, the EPA-approved PBPK model simulates how long it will take the human arterial blood concentration to reach the critical arterial blood concentration (as determined in the dog test) during human inhalation of any particular concentration of the halocarbon agent.

2.1.2 Subchronic and Chronic Tests.

2.1.2.1 Ninety-Day Subchronic Toxicity Test.

The 90-day subchronic toxicity test is an assay that determines changes due to repeated and prolonged chemical exposure. Subchronic toxicity testing is one of the studies for developing industrial exposure standards.

2.1.2.2 Chronic Toxicity Testing.

Chronic toxicity tests are conducted over the greater part of the animal's lifespan (1.5 to 2 years in mice and 2 or more years in rats), starting at weaning, with daily exposure to the test agent. The principal endpoint is tumor formation, as determined by histological exam.

2.1.2.3 Carcinogenicity Screening.

Chemical carcinogenesis is usually the result of long-term exposure to a chemical. To determine the potential for long-term toxicity and possible carcinogenicity, genotoxicity (mutagenicity) tests are often performed. Positive results, i.e., the chemical produced a mutagenic effect, alert toxicologists to the possibility of long-term effects including carcinogenicity. The following genotoxicity tests are most often used.

2.1.2.4 Ames Test.

The Ames test, an *in vitro* test for mutagenicity and, by implication, carcinogenicity, uses mutant strains of bacterium *Salmonella typhimurium* as a preliminary screen for carcinogenic potential [22]. A number of strains of *S. typhimurium* comprise the Ames test, and positives indicate that a mutation in the genetic material has occurred. Mutagenic and presumed carcinogenic materials cause genetic mutations that allow the bacterial strains to grow in a histidine-free medium.

2.1.2.5 Mouse Lymphoma Test.

The mouse lymphoma test, also an *in vitro* screening test, uses cell cultures of mouse lymphoma cells. The mutagenic potential of a material is tested by observing the ability to confer resistance within this cell line to normally toxic agents. Mutations in the genetic material allow the cells to grow in the presence of other known toxic materials (purines, pyrimidines, or ouabain). Promutagens (mutagenic agents that require metabolic activation) can also be identified.

2.1.2.6 Mouse Micronucleus Test.

The mouse micronucleus test, an *in vivo* test, determines the potential of a chemical to cause chromosome breakage or interference with normal cell division. The test entails exposing live mice to the test material, removing premature red blood cells from the bone marrow, and observing the cells for the presence of chromosome fragments or the lack of signs of normal cell division. This test is not considered the most sensitive test for chromosomal aberrations.

2.1.2.7 Other Screening Tests.

Other *in vitro* tests that yield information on the carcinogenic potential of an agent include the unscheduled deoxyribonucleic acid (DNA) synthesis test, the sex-linked recessive mutation test, and the sister chromatid exchange test. The unscheduled DNA synthesis (UDS) test involves the exposure of cultured hepatocytes (liver cells) to the test chemical and monitors the repair of DNA following DNA damage by a mutagen. The sex-linked recessive mutation test for mutagenicity utilizes *Drosophila melanogaster* (fruit fly) males with a marker (yellow body) on the X chromosome. The sister chromatid exchange test, which can also be an *in vivo* test, detects DNA alkylating agents in Chinese hamster ovary cells.

The *in vivo* dominant lethal (rodent) test assesses the ability of a suspected mutagen, which has shown positive in an *in vitro* screen, to cause dominant lethal mutations in rats, mice, or hamsters. Male rodents are treated with the test substance and are then mated to groups of females over several weeks to test for effects occurring at all stages of sperm formation. Following sacrifice, the females are evaluated for a number of fertility indices.

2.1.2.8 Interpretation of Carcinogenicity Results.

For years the predictive value of short-term *in vitro* mutagenicity tests for potential carcinogenicity has been questioned [23]. The degree to which the results of these short-term assays correlate with carcinogenicity in whole animals resulting in actual tumor formation largely depends on chemical class. For fluorinated hydrocarbons, the correlation has not proved to be exact.

2.1.3 Exposure Limits.

Four major noncommercial organizations (two governmental and two nongovernmental) establish or recommend occupational exposure limits. The National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) are governmental organizations. Standards established under OSHA are enforceable, whereas NIOSH only sets recommended occupational exposure limits. The American Conference of Governmental Industrial Hygienists (ACGIH) and the American Industrial Hygiene Association (AIHA) are nongovernmental organizations that establish exposure limits. Table 4 gives the various types of exposure limits that have been established by these organizations. The only exposure limits actually used by industrial hygienists are the Permissible Exposure Limit (PEL), the Workplace Environmental Exposure Limit (WEEL), and the Threshold Limit Value (TLV), which all are the appropriate upper exposure limit for safe handling over a lifetime of occupational exposure (e.g., industrial processing rather than firefighting). The Acceptable Exposure Limit (AEL), which is widely cited, was originally used by DuPont; however, it is now given by a number of other commercial organizations. The Occupational Exposure Limit is similar to the other limits but can be established by any organization.

TABLE 4. EXPOSURE LIMIT DEFINITIONS

Exposure Limit		Establishing Organization	Definition
Long-Term Exposures			
AEL	Acceptable Exposure Limit	Commercial	
OEL	Occupational Exposure Limit	Any	Similar to PEL but not enforceable.
PEL	Permissible Exposure Limit	OSHA	Enforceable 8-hour Time-Weighted Average (TWA) exposure limit for airborne substances intended to reduce a significant risk of health or functional capacity impairment.
REL	Recommended Exposure Limit	NIOSH	Similar to TLV values.
TLV	Threshold Limit Value	ACGIH	TWA exposure limits similar to PEL values.
WEEL	Workplace Environmental Exposure Limit Guide	AIHA	Similar to TLV values.
WGL	Workplace Guidance Level	EPA	Eight-hour per day TWA value analogous to PEL values.
Short-Term Exposures			
CL	Ceiling Level	OSHA	Enforceable exposure level that cannot be exceeded for any time period.
STEL	Short-Term Exposure Limit	OSHA	Enforceable 15-minute TWA exposure that should not be exceeded at any time during a workday.
IDLH	Immediately Dangerous to Life and Health	NIOSH	Maximum concentrations from which one could escape within 30 minutes without experiencing escape-impairing or irreversible health effects.
EGL	Emergency Guidance Level	EPA	Applies to a short-term exposure of 15 or 30 minutes and is similar to the IDLH.

TABLE 4. EXPOSURE LIMIT DEFINITIONS (Continued)

Exposure Limit		Establishing Organization	Definition
ERPG 1	Emergency Response Planning Guideline, Level 1	AIHA	Maximum airborne concentration below which it is believed nearly all individuals could be exposed up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor. ^a
ERPG 2	Emergency Response Planning Guideline, Level 2	AIHA	Maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action. ^a
ERPG 3	Emergency Response Planning Guideline, Level 3	AIHA	Maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects. ^a

^a Reference 24.

Of greater importance in fire protection are the limits established for exposure during agent discharge. Two somewhat differing sets of criteria have been established for total flood protection. The 2000 edition of the National Fire Protection Association (NFPA) Standard 2001 [21] requires that the design concentration for total flooding of a normally occupied area by halocarbons not exceed the cardiac sensitization NOAEL. In addition, halocarbon agent concentrations above 24 percent are not allowed in normally occupied areas. The Standard calls for avoidance of unnecessary exposure to agents covered in the Standard and for suitable safeguards to ensure prompt evacuation. Audible and visual predischage alarms are required. New methods to determine limits on exposures and egress times using a physiologically based pharmacokinetic (PBPK) model are included in the Standard. Halocarbon systems for spaces that are normally occupied and designed for concentrations above the NOAEL and up to the LOAEL shall be permitted, given that means be provided to limit exposure to no longer than the time specified. In spaces that are not normally occupied and protected by a halocarbon system designed for concentrations above the LOAEL and where personnel could possibly be exposed, means shall be provided to limit exposure times using tables in the NFPA 2001 Standard. In the

absence of the information needed to fulfill the conditions listed above, the following provisions shall apply.

1. Where egress takes longer than 30 seconds but less than 1 minute, the halocarbon agent shall not be used in a concentration exceeding its LOAEL.
2. Concentrations exceeding the LOAEL are permitted only in areas not normally occupied by personnel provided that any personnel in the area can escape within 30 seconds. No unprotected personnel shall enter the area during agent discharge.

The EPA SNAP program uses the cardiotoxic LOAEL value to assess use of an agent in normally occupied areas [9]. In the past, the EPA has established use conditions for total flooding agents used for fire suppression based on OSHA regulation 1910.162 [25]. The EPA is preparing to replace these restrictions on exposure limits and egress times for halocarbon and inert gas total flooding agents and to recommend compliance with the 2000 version of the NFPA 2001 Standard. The 2000 version of the Standard is based on new and more precise risk assessment procedures [26] (PBPK model) that bridge toxicological research on animals to actual concentrations measured in humans. The EPA will revise the SNAP listings for halocarbons and inert gas agents to include the comment: "Use of this agent should be in accordance with the safety guidelines in the latest edition of NFPA 2001 Standard for Clean Agent Fire Extinguishing Systems." The EPA expects to make these changes to the SNAP regulations available for public comment in early 2002 [27].

The New Extinguishants Advisory Group (NEAG), a subgroup of the Halon Alternatives Group (HAG) in the U.K., has attempted to base allowable design concentrations for automatic systems in occupied areas on six endpoints: LC_{50} , CNS effects, cardiac sensitization, respiratory sensitization, genotoxicity, and developmental toxicity [28]. For the three halocarbon agents that they evaluated, NEAG found that cardiac sensitization or, in the case of very low-toxicity agents, hypoxia are the critical endpoints. At a recent HAG meeting, it was agreed to use the PBPK model [29].

2.2 ENVIRONMENTAL CONSIDERATIONS.

2.2.1 Ozone Depletion Potential.

Ozone Depletion Potentials (ODPs) are the calculated ozone depletions per unit mass of material released relative to a standard, normally CFC-11. It should be noted that ODPs are calculated; they cannot be measured. Although calculations of ODPs require time horizons (see section 2.2.3), steady-state calculations have generally been used. Although ODPs vary somewhat, depending on the calculation method, it is believed that relative values for compounds containing the same ozone-depleting element are relatively reliable. Thus, halocarbons that contain only chlorine and fluorine (in addition to carbon and, possibly, hydrogen) can be compared to CFC-11. It is well-established that bromine is much more damaging to ozone than is chlorine on a per atom basis. Exactly how much more, however, is not precisely known and lends some uncertainty to the ODPs of bromocarbons. The model calculations used by the U.S. EPA

incorporate an effect ratio of 55 chlorine atoms to 1 bromine atom. An excellent nontechnical historical overview is contained in reference 30.

2.2.2 Atmospheric Lifetime.

Atmospheric lifetimes are generally modeled as e-folding lifetimes. The gas concentration decays exponentially following the equation

$$C_t = C_0 e^{-t/L}$$

where C_0 is the initial concentration, C_t is the concentration at any time t , and L is the atmospheric lifetime. After one lifetime, the gas concentration drops to $1/e$ (approximately 0.369) of its initial value. Note that this equation predicts that the concentration will never reach zero, although it can approach it very closely. For example, after only five lifetimes, the concentration drops to 0.0067 of its initial value.

2.2.3 Global Warming Potential.

The GWP is the change in radiative forcing resulting from the emission of 1 kilogram of a chemical relative to the radiative forcing resulting from the emission of 1 kilogram of a reference gas. In the past, CFC-11 was often used as the reference; however, carbon dioxide (CO_2) is now typically used. The global warming potential depends on three variables: (1) the location of the IR absorption bands, (2) the strength of the IR absorption bands, and (3) the lifetime of the gas. It is important to note that the GWP can vary significantly depending on the time period used for the comparison of the radiative forcing of the chemical relative to that of the reference. The time period used to calculate the GWP is termed the time horizon and is primarily a policy decision. Time horizons of 100 and 500 years are often used in calculated GWP values; however, other time horizons may be more appropriate. GWPs with longer time periods are believed to be more inaccurate than those with shorter times periods [31]. All GWPs in this report are 100- and 500-year time horizon values referenced to carbon dioxide.

2.2.4 Atmospheric Impacts of Blends.

Some replacement agents are blends of more than one component. The atmospheric impacts of blends should be evaluated by looking at the ODP, GWP, and the atmospheric lifetime of each component separately because each component acts independently when released to the atmosphere even if it has been blended with other components. The atmospheric effects of an individual component in a blend have the same impact as if the individual component were released to the atmosphere as a pure substance.

Some manufacturers calculate and report averages of ODP, GWP, and/or atmospheric lifetime for a blend. Other manufacturers do not identify all components and use the environmental characteristics of a principal component to represent the atmospheric impact of a blend. Neither the parties to the Montreal Protocol nor government agencies such as the U.S. Environmental Protection Agency accept such practices as representing an accurate evaluation of the atmospheric impact. Instead, such groups and organizations use the ODP, GWP, and atmospheric lifetime of each component to evaluate the overall atmospheric impact of a blend.

2.2.5 Regulatory Restrictions.

Under the Montreal Protocol, production of the most commonly used halons (Halon 1301, 1211, and 2402) ceased on 1 January 1994 in industrialized (non-Article-5) nations (see table 5). Non-industrialized (Article 5) nations have until 1 January 2010 (10 years from the date of the London Amendment schedule) to phase out halon production. In the U.S., the Clean Air Act implements the Montreal Protocol (see table 6) [32]. Under the Protocol, "consumption" is defined as the amount produced by a country minus exports plus imports. Thus, consumption is essentially the same as production.

TABLE 5. REDUCTIONS IN MAXIMUM ALLOWABLE CONSUMPTION UNDER THE MONTREAL PROTOCOL AS AMENDED IN 1995

Year ^a	CFCs	Halons	Methyl Chloroform	Carbon Tetrachloride	Methyl Bromide	HCFCs	HBFCs
1994	75%	100%	50%				
1995				85%	Cap ^b		
1996	100%		100%	100%		Cap ^b	100%
1999					25%		
2001					50%		
2003					70%		
2004						35%	
2005					100%		
2010						65%	
2015						90%	
2020						99.5%	
2030						100%	

^a Beginning January 1 of the year cited, the annual consumption amounts (essentially, the amount produced) must meet the prescribed cuts. The base years are CFCs in original Protocol, 1986; CFCs in 1990 amendment, 1989; halons, 1986; methyl chloroform and carbon tetrachloride, 1989; and methyl bromide, 1991. The base for HCFCs is the 1989 ODP-weighted HCFC consumption plus 2.8% of the 1989 ODP-weighted CFC consumption.

^b Freezing at specific year levels.

TABLE 6. CONTROLS UNDER CLEAN AIR ACT AMENDMENTS OF 1990

Ozone-Depleting Chemicals	Baseline Year	Allowed Production	
		January	Percent of Base Year ^a
Class I Substances			
Group I: CFC-11, 12, 113, 114, 115	1986	1994	25
		1995	25
		1996	0
Group II: Halon 1211, 1301, 2402	1986	1994	0
Group III: CFC-13, 111, 112, 211, 212, 213, 214, 215, 216, 217	1989	1994	25
		1995	25
		1996	0
Group IV Carbon Tetrachloride	1989	1994	50
		1995	15
		1996	0
Group V Methyl Chloroform	1989	1994	50
		1995	30
		1996	0
Group VI Methyl Bromide	1991	1994	100
		1995	100
		1996	100
		1997	100
		1998	100
		1999	75
		2001	50
		2003	30
		2005	0
Group VII HBFCs	1991	1994	100
		1995	100
		1996	0
Class II Substances ^b			
HCFC-141b	^c	2003	0
HCFC-22, -142b	^c	2010	100
		2020	0
HCFC-123, -124, remaining HCFCs	^c	2015	100
		2030	0

^a 100% denotes a freeze in production to the base year.

^b HCFC-22 and -142b can be produced between 2010 and 2020 only to service equipment manufactured prior to 1 January 2010. HCFC-123, -124, and remaining HCFCs can be produced between 2015 and 2030 only to service appliances manufactured prior to 1 January 2020. The HCFC controls do not apply to used or recycled HCFCs, HCFCs used as feedstocks, or HCFCs for use in a process that transforms or destroys the chemical.

^c The base for HCFCs is the 1989 ODP-weighted HCFC consumption plus 2.8% of the 1989 ODP-weighted CFC consumption.

2.3 COMMERCIALIZED HALOCARBON REPLACEMENTS.

Here, the term commercialized is used to refer to materials now being marketed or which are planned to be marketed in the near future. Most of the commercialized agents are PAAs—hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), or perfluorocarbons (FCs or PFCs). The only CAA now being commercialized is CF₃I.

HCFCs have a nonzero ODP and currently face an eventual regulated production phase out. Some restrictions are already in place in parts of Europe. The European Union in many cases has accelerated phaseout dates. The current regulations can be found on the website of the European Communities [33]. Another useful site is the European Union's website on ozone layer protection [34].

Under the SNAP program, the EPA has applied narrowed use limits to the use of perfluorocarbons. PFCs are fully fluorinated compounds, unlike HCFCs or HFCs, and have several attractive features. They are nonflammable, have low toxicity, are exempt from federal volatile organic hydrocarbons (VOC) regulations, and do not contribute to stratospheric ozone depletion. The environmental characteristics of concern, however, are their high global warming potentials (approximately 5,000 to 10,000 times that of CO₂ for commercialized halon replacements) and their long atmospheric lifetimes (approximately 5,000 to 7,000 years for commercialized replacements). As the time horizon increases, the GWP for these compounds also increases, making these compounds particularly undesirable. Although the actual contributions to global warming depend upon the quantities emitted, the long lifetimes make the warming effects of PFCs virtually irreversible. The EPA is allowing the use of PFCs for only selected applications where no other substitutes are technically feasible due to performance or safety requirements. Because of the concerns about their long atmospheric lifetimes and high GWP, 3M has pulled out of this business. At a recent Fire Protection subcommittee meeting of the International Maritime Organization (IMO), it was pointed out that new installation of fire suppressant where good fire engineering can be employed, made the use of PFCs unnecessary. The Maritime Safety Circular (MSC) prohibits the use of PFCs in new shipboard fire suppression systems, since they determined that there are no essential marine uses for PFCs [35].

HFCs are attractive as replacements for ozone depleting substances for three reasons: (1) they are usually volatile and many have low toxicities, (2) they are not ozone depleting as are the HCFCs and because they have lower atmospheric lifetimes than PFCs, they are likely to receive less regulatory action than HCFCs or PFCs, and (3) they have properties similar to those of halocarbons that have been used in the past. This does not, however, mean that HFCs are not receiving scrutiny from environmental organizations. A recent study by the National Institute of Public Health and Environmental Protection, The Netherlands, has projected a significant increase in greenhouse gas emissions due to use of HFCs to replace CFCs and HCFCs [36]. Moreover, Denmark has announced they plan to phase out all hydrofluorocarbons (HFCs) within the next 10 years (written in 1996) due to global warming [37]. Other European countries such as Austria and Norway are considering regulation of HFC use [38].

Of particular interest is that halocarbons other than Halons 1211 and 1301 are banned from all fire protection equipment in Denmark other than that used by the Fire Brigade [39].^a Denmark is leading the promotion of natural (nonhalocarbon) fire extinguishants (water sprinklers and mist, carbon dioxide, dry chemical, foam, and inert gases [40]).

A large number of candidate replacement agents have been announced for commercialization, and even more chemicals are under serious consideration. A number of halocarbon replacements have been announced for total-flood applications (see table 7). All of these agents are contained in the NFPA 2001 Standard [21].

TABLE 7. COMMERCIALIZED TOTAL-FLOOD AGENTS

Agent	Chemical	Formula	Trade Name
Halon 1301	Bromotrifluoromethane	CBrF_3	
HCFC-124	Chlorotetrafluoroethane	CHClFCF_3	DuPont FE-241
HCFC Blend A HCFC-123 HCFC-22 HCFC-124	Additive plus Dichlorotrifluoroethane Chlorodifluoromethane Chlorotetrafluoroethane	CHCl_2CF_3 CHClF_2 CHClFCF_3	North American Fire Guardian NAF S-III
HFC-23	Trifluoromethane	CHF_3	DuPont FE-13
HFC-125	Pentafluoroethane	CHF_2CF_3	DuPont FE-25
HFC-227ea	Heptafluoropropane	$\text{CF}_3\text{CHFCF}_3$	Great Lakes FM-200 DuPont FE-227
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$\text{CF}_3\text{CH}_2\text{CF}_3$	DuPont FE-36
FC-218	Perfluoropropane	$\text{CF}_3\text{CF}_2\text{CF}_3$	3M CEA-308
FC-3-1-10	Perfluorobutane	$\text{CF}_3\text{CF}_2\text{CF}_2\text{CF}_3$	3M Company CEA 410
FIC-13I1	Trifluoroiodomethane	CF_3I	West Florida Ordnance Iodoguard; Ajay North America

The design concentrations for total-flood fire extinguishment for *n*-heptane, a standard fuel, are shown in table 8. These design concentrations are, in general, determined as the cup burner extinguishment concentration increased by a safety factor of 30 percent; though the results of other testing may be taken into account. Both the International Standards Organization (ISO) standard on gaseous fire extinguishing agents [41] and the 2000 edition of the NFPA 2001 standard [21] require a safety factor of 30 percent. The information for this table was compiled from (1) information from manufacturers and (2) the NFPA 2001 Standard [21] and the NFPA 12A Standard [42]. These design concentrations are minimum manufacturer-recommended values for extinguishment of Class B fires with *n*-heptane fuel and are determined as 130 percent of the cup burner value for *n*-heptane.

^a The original decree mistakenly listed three bromocarbons allowed, none of which were Halon 1211 or 1301. These were "difluoromonobrometan, difluordibrommetan eller trifluoromonometan" (difluoromonobromomethane, difluorodibromomethane or trifluoromonomethane [sic]). A later amendment corrected this list to Halons 1211 and 1301, the only two halocarbons whose use was requested by fire equipment manufacturers in Denmark.

TABLE 8. DESIGN CONCENTRATIONS OF COMMERCIALIZED TOTAL-FLOOD AGENTS (30 Percent Safety Factor)

Agent	Minimum Design Concentration for <i>n</i> -heptane, % ^d	Maximum Fill Density, kg/m ³ (lb/ft ³) ^d	Storage Pressure at 21.1°C (70°F), bar (psi) ^{a,d}
Halon 1301	5 ^b	1121 (70) ^c	24.8 (360) ^c
HCFC-124	8.6	1137 (71.0)	13.4 (195)
HCFC Blend A	12.9	900 (56.2)	24.8 (360)
HFC-23	16.8	865 (54.0) ^g	42.0 (608.9) ^e
HFC-125	11.3	929 (58.0)	11.5 (166.4) ^e
HFC-227ea	8.5	1153 (72.0)	24.8 (360)
HFC-236fa	8.2	1249 (78) ^f	1.27 (18.4) ^{e,f}
FC-218	8.5	1281 (80) ^f	24.8 (360) ^f
FC-3-1-10	7.2	1281 (80.0)	24.8 (360)
FIC-1311	4.2	1677 (104.7)	24.8 (360)

^a Unless otherwise noted, storage pressures are with nitrogen pressurization.

^b The design concentration for Halon 1301 is that set by NFPA Standard 12A [42] and is higher than the value of approximately 3.9% determined by 130% of the cup burner value.

^c Reference 42

^d Except where noted, calculated from data in NFPA 2001 and 12A [21 and 42].

^e This is the actual equilibrium pressure within the container due to the vapor pressure of the agent alone (i.e., without nitrogen pressurization).

^f Data does not appear in the current NFPA 2001 Standard. Information provided by manufacturer.

^g HFC-23 has a critical point near room temperature. Because of this, HFC-23 is not stored based on the "normal" DOT regulations for liquified compressed gases (hot liquid falls at 130°F), there is a DOT exception for HFC-23. The fill density reflects this storage uniqueness.

Design concentrations may differ for other fuels and will be higher for inertion of an area. Some users are planning to employ or are employing some agents at considerably higher concentrations than the minimum recommended values based on the specific fuel, scenario, and threat. U.S. Navy researchers feel that realistic design concentrations must be determined by tests at a realistic scale [43]. Such tests have shown that, although design concentrations at 20 percent above cup burner can extinguish large turbulent pool fires, these minimum concentrations increase the time required to effect extinguishment and generate extensive decomposition products [44]. In fact, based on the inclusion of safety and other factors [45], the U.S. Navy plans to employ design concentrations from 50 to 70 percent above the value shown for one agent in table 8 in at least some shipboard applications [43]. Work at the Federal Aviation Administration William J. Hughes Technical Center indicates that required concentrations of Halon 1301 in aircraft exceed 130 percent of the cup burner concentrations, that even the required concentrations may not be adequate for all fires, and that the same level or greater of protection must be demonstrated to determine the acceptable concentration of a replacement agent. Extensive testing of Class A cargo fires at the FAA has shown that reignition occurs for

suppressed fires for some replacement agents when the compartment is maintained at concentrations lower than the inerting concentration [46]. Similarly, extensive testing of Class A and Class B fires by the UK Loss Prevention Council shows failures to extinguish fires in some tests for some agents and excessive formation of decomposition products for halocarbons and, in some cases, using the design concentrations recommended at the time that the work was done and with systems provided by commercial equipment manufacturers [47]. Some recommended design concentrations have since been increased. All of this indicates that required concentrations of halocarbon replacement agents may, under some circumstances exceed the concentrations shown in table 8.

Table 9 gives weight and storage volume equivalents relative to Halon 1301 for design concentrations of agent. The weight equivalent is the weight of agent required divided by the weight of Halon 1301 required. The storage volume equivalent is the storage volume of agent required divided by the storage volume of Halon 1301 required. Three things must be noted. First, the storage volume equivalent is different from the simple ratio of the design concentrations. The storage volume equivalent takes into account the volume occupied by the agent (usually, but not always, a liquid) when contained in a cylinder. Second, this definition results in different values than one would obtain if extinguishing concentrations rather than design concentrations were used because the design concentration for Halon 1301 is more than 130 percent of its extinguishing concentration. In general, this makes the storage volume and weight equivalents lower than would be predicted from the cup burner value or some other measure of extinguishing efficiency. Third, these equivalents are based on the minimum manufacturer-recommended design concentrations for an *n*-heptane fire and larger design concentrations may be used in some applications based on fuel, scenario, and threat. Thus, the values for equivalents in table 9 are minimum values.

The weight and storage volume equivalents for design concentrations of total-flood agents for *n*-heptane fires are listed in table 9. The weight equivalents were calculated from the total-flood specific weights (weight/unit volume) at 70°F given in NFPA Standards 2001 and 12A [21 and 42] for the *n*-heptane design concentrations and maximum fill densities given in table 8. In this case, the weight equivalent = (W_a/W_{1301}) , where W_a and W_{1301} are the total-flood specific weights for the agent of interest and Halon 1301 (0.0206 lb/ft³ at a design concentration of 5 percent at 70°F [42]), respectively. The specific weights are taken from tables in the NFPA Standards 2001. These specific weights include an allowance for normal leakage from a tight enclosure. The storage volume equivalent is then the product of the weight equivalent and the ratio (D_{1301}/D_a) , where D_a and D_{1301} are the maximum fill densities for the agent of interest and Halon 1301. Note that the equivalents are based on a Class B *n*-heptane fire and may be different for Class A fires and for Class B fuels other than *n*-heptane.

Another method for determining the weight and storage volume equivalents is to directly calculate the values from the laboratory-determined properties. This method does not use the specified design concentration or the fill densities; however, it does more closely compare the actual agent performance to that of Halon 1301. The results are shown in table 10. The extinguishment concentrations are cup burner values taken from a single source [21]. Note that the number of significant figures for the equivalents is larger than justified by the extinguishment concentration precision.

TABLE 9. WEIGHT AND STORAGE VOLUME EQUIVALENTS FOR DESIGN CONCENTRATIONS OF TOTAL-FLOOD AGENT FOR *n*-HEPTANE FIRES (30 percent safety factor)

Agent	Normal Leakage (Calculated From Weight Requirements and Fill Densities)		
	Weight Equivalent ^a	Storage Volume Equivalent ^a	Molecular Weight
Halon 1301	1.00	1.00	148.93
HCFC-124	1.67	1.64	136.48
HCFC Blend A	2.20	2.74	92.90
HFC-23	1.79	2.32	70.01
HFC-125	1.95	2.36	120.02
HFC-227ea	2.03	1.97	170.03
HFC-236fa	1.76	1.58	152.04
FC-218	2.20	1.92	188.03
FC-3-1-10	2.30	2.01	238.03
FIC-131I	1.06	0.71	195.91

^a Calculated from data in NFPA Standards 2001 and 12A [21 and 42] and table 8.

TABLE 10. COMPARATIVE PERFORMANCE OF TOTAL-FLOOD REPLACEMENTS FOR *n*-HEPTANE FUEL

Agent	Cup Burner Extinguishment Concentration, vol%	Molecular Weight	Liquid Density, ^a g/mL, 25°C	Weight Equivalent	Storage Volume Equivalent
Halon 1301	3.4	148.93	1.551	1.00	1.00
HCFC-124	6.6	136.48	1.357	1.81	2.06
HCFC Blend A	9.9	92.90	1.20	1.82	2.25
HFC-23	12.9	70.01	0.685 ^b	1.80	4.07
HFC-125	8.7	120.02	1.190	2.11	2.75
HFC-227ea	6.5	170.03	1.395	2.22	2.46
HFC-236fa	6.3	152.04	1.356	1.89	2.16
FC-218	6.5	188.02	1.321	2.26	2.66
FC-3-1-10	5.5	238.03	1.497	2.49	2.58
FIC-131I	3.2	195.91	2.106	1.24	0.91

^a Reference 48

^b HFC-23 has a critical point near room temperatures, and it is difficult to define a single density. Use caution in interpreting storage volume equivalents calculated here.

The environmental and toxicity properties of commercialized total-flood agents are shown in table 11. All agents other than Halon 1301 listed in table 11 are acceptable under SNAP; however, there are limitations on its use for certain agents (see table footnotes).

TABLE 11. ENVIRONMENTAL AND TOXICITY PROPERTIES OF COMMERCIALIZED TOTAL-FLOOD AGENTS

Agent	ODP ^a	GWP ^{b,c} (100 years)	GWP ^{b,c} (500 years)	Atmospheric Lifetime, ^c (yrs)	NOAEL ^e (%)	LOAEL ^e (%)
Halon 1301	12	6,900	2,700	65	5 ^d	7.5 ^d
HCFC-124	0.026	620	190	6.1	1.0	2.5
HCFC Blend A	0.044 ^f	1,450 ^f		12 ^f	10.0	>10.0
HCFC-123	0.012 ^a	120	36	1.4	1.0 ^g	2.0 ^g
HCFC-22	0.034 ^a	1,900	590	11.8	2.5 ^g	5.0 ^g
HCFC-124	0.086 ^a	620	190	6.1	1.0	2.5
HFC-23	0.0 ^h	14,800	11,900	243	50	>50
HFC-125	0.0 ^h	3,800	1,200	32.6	7.5	10.0
HFC-227ea	0.0 ⁱ	3,800	1,300	36.5	9.0	10.5
HFC-236fa ⁱ	0.0 ⁱ	9,400	7,300	226	10.0	15.0
FC-218 ^j	0.0 ⁱ	8,600	12,400	2,600	30	>30
FC-3-1-10 ^j	0.0 ⁱ	8,600	12,400	2,600	40	>40
FIC-1311 ^k	<0.008	<1	<<1	0.005	0.2	0.4

^a Relative to CFC-11. From reference 49, except where otherwise noted.

^b Based on a time horizon, relative to CO₂.

^c Reference 49.

^d References 21 and 50. Note that EPA accepts NOAEL and LOAEL values of 7.5% and 10% based on other sources [51].

^e From reference 21 unless otherwise noted.

^f Calculated by the manufacturer from a weighted average for the blend components. These calculations are based on older data for the individual components. The use of averaged data is not accepted by most organizations in establishing impacts (see section 2.2.4).

^g Reference 10.

^h The actual ODPs of HFC-23 and HFC-125 are given as $<4 \times 10^{-4}$ and $<3 \times 10^{-5}$, essentially zero. It is likely that all HFCs have a small, but nonzero ODP.

ⁱ Acceptable under SNAP for fire suppression in nonresidential use only when other non-PFC alternatives are not technically feasible due to performance or safety requirements [12]. There is no similar restriction for explosion inertion and suppression.

^j PFCs are acceptable under SNAP for nonresidential use only when other alternatives are not technically feasible due to performance or safety requirements [12]. The GWP increases for the PFCs as the time horizon increases.

^k Acceptable under SNAP for protection of nonoccupied areas only [12].

^l From Reference 48.

Until recently, the number of agents announced for streaming applications was small. The number has, however, increased markedly (table 12). Some environmental and toxicological data for these streaming agents are given in table 13. All agents other than Halon 1211 listed in this table are acceptable or proposed acceptable under SNAP with use limitations for some (see table footnotes).

TABLE 12. COMMERCIALIZED STREAMING AGENTS

Agent	Chemical	Formula	Trade Name
Halon 1211	Bromochlorodifluoromethane	CBrClF_2	
HCFC-123	Dichlorotrifluoroethane	CHCl_2CF_3	DuPont FE-232
HCFC-124	Chlorotetrafluoroethane	$\text{CHClF}_2\text{CF}_3$	DuPont FE-241
HCFC Blend B ^a PFC-14 HCFC-123	Proprietary blend of Tetrafluoromethane Dichlorotrifluoroethane	CF_4 CHCl_2CF_3	American Pacific Halotron I
HCFC Blend C HCFC-123 HCFC-124 HFC-134a	Proprietary additive plus Dichlorotrifluoroethane Chlorotetrafluoroethane 1,1,1,2-Tetrafluoroethane	CHCl_2CF_3 $\text{CHClF}_2\text{CF}_3$ CH_2FCF_3	North American Fire Guardian NAF P-III
HCFC Blend D HCFC-123	Proprietary additive plus Dichlorotrifluoroethane	CHCl_2CF_3	North American Fire Guardian BLITZ
HCFC Blend E	Proprietary formulation of HCFC, HFC, and additive		North American Fire Guardian NAF P-IV
HFC-227ea	Heptafluoropropane	$\text{CF}_3\text{CHF}_2\text{CF}_3$	Great Lakes FM-200
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$\text{CF}_3\text{CH}_2\text{CF}_3$	DuPont FE-36
FC-5-1-14	Perfluorohexane	$\text{CF}_3(\text{CF}_2)_4\text{CF}_3$	3M Company CEA 614 ^b
FIC-13I1	Trifluoroiodomethane	CF_3I	West Florida Ordnance Iodoguard; Ajay North America

^a This agent is charged with argon, not nitrogen as the propellant.

^b 3M has pulled out of the business because of concerns of about their long atmospheric lifetimes and high GWPs.

TABLE 13. ENVIRONMENTAL AND TOXICITY PROPERTIES OF COMMERCIALIZED STREAMING AGENTS

Agent	ODP ^a	GWP ^{b,c} (100 years)	GWP ^{b,c} (500 years)	Atmospheric Lifetime, ^c (yrs)	NOAEL (%)	LOAEL (%)
Halon 1211	5.1	1300	390	11	0.5 ^d	1.0 ^d
HCFC-123	0.012	120	36	1.4	1.0 ^e	2.0 ^e
HCFC-124	0.026	620	190	6.1	1.0 ^f	2.5 ^f
HCFC Blend B ^g						
PFC-14	ⁱ	5700	8900	50,000	>30 ^f	>30 ^f
HCFC-123	0.012	120	36	1.4	1.0 ^e	2.0 ^e
HCFC Blend C						
HCFC-123	0.012	120	36	1.4	1.0 ^e	2.0 ^e
HCFC-124	0.026	620	190	6.1	1.0 ^f	2.5 ^f
HFC-134a	0.0 ^h	1600	500	13.6	4.0 ^e	8.0 ^e
HCFC Blend D						
HCFC-123	0.012	120	36	1.4	1.0 ^e	2.0 ^e
HCFC Blend E	ⁱ	ⁱ	ⁱ	ⁱ	ⁱ	ⁱ
HFC-227ea	0.0 ^k	3800	1300	36.5	9.0 ^f	10.5 ^f
HFC-236fa	0.0 ^k	9400	7300	226	10.0 ^f	15.0 ^f
FC-5-1-14 ^j	0.0 ^k	9000	13200	3200	40 ^e	>40 ^e
FIC-13I1	<0.008	<1	<<1	0.005	0.2 ^f	0.4 ^f

^a Relative to CFC-11. From reference 49 except where otherwise noted.

^b Based on a time horizon, relative to CO₂.

^c Reference 49.

^d Reference 52.

^e Reference 10.

^f Reference 21.

^g The amount and type of PFC must be considered when assessing the environmental impact (see section 2.2.4). This blend contains a PFC in small proportions.

^h Actually <1.5 x 10⁻⁵, essentially zero. It is likely that all HFCs have a small but nonzero ODP.

ⁱ Data not available.

^j PFCs are acceptable under SNAP for nonresidential use only when other alternatives are not technically feasible due to performance or safety requirements.

^k Reference 48.

^l Reference 53.

All of the halocarbon agents have tradeoffs for total-flood and/or streaming applications. As noted earlier, halon replacements should have four characteristics: a low global environmental impact, acceptable toxicity, cleanliness/volatility, and effectiveness. Though it is very easy to find candidate replacements that meet any three of these criteria, it has been difficult to find agents that meet all four. For most (but not all) applications, significantly more replacement agent is needed to provide the same degree of protection as provided by the present halons. The exception is FIC-13I1, which has total-flood use limitations owing to toxicity.

One potential problem that occurs with many (but not all) of the new halocarbon agents is that they generate four to ten times more hydrogen fluoride (HF) than Halon 1301 does during comparable extinguishment [13 and 54]. Although a large amount of information is available on hydrogen fluoride toxicity [55 and 21], it is difficult to determine what risk is acceptable. A good review of the toxicity of HF as it relates to short exposures of high concentration of HF can be found in the NFPA 2001 Appendix [21]. Some data exists to determine what hydrogen fluoride levels are likely in real fire scenarios. In general, agent decomposition products and combustion products increase with fire size and extinguishment time [56 and 21]. To minimize decomposition and combustion products, early detection and rapid discharge are recommended.

The effects of HF will occur at the site of contact and will be observed as inflammation (irritation) that can progress to severe, deep-penetrating irritation. At high concentrations of HF (>200 ppm) for an extended duration of time, e.g., 1 hour, fatalities may occur, particularly in the absence of any medical treatment.

At concentrations of <50 ppm for up to 10 minutes, definite irritation of upper respiratory tract, skin, and eyes would be expected to occur. At these low concentrations, escape-impairing effects would not be expected in the healthy individual. As HF concentrations increase to 50 to 100 ppm, an increase in irritation is expected. At 100 ppm for 5 minutes, moderate irritation of all tissue surfaces would be expected, and as the duration of exposure increases to 10 minutes, escape-impairing effects would begin to occur. As the concentration of HF increases, the severity of irritation, including escape-impairing irritation of the eyes and respiratory tract, increases and the potential for delayed systemic effects also increases. At these higher concentrations, humans would be expected to shift to mouth breathing, and deeper lung irritation is expected. At greater concentrations (>200 ppm), respiratory discomfort, pulmonary (deep lung) irritation, and systemic effects are possible. Continued exposure at these concentrations may be lethal in the absence of medical treatment.

The American Industrial Hygiene Association (AIHA) Emergency Response Planning Guideline (ERPG) represents limits established for emergency release of chemicals [24]. These limits are established to also account for sensitive populations, e.g., those with compromised health. The ERPG limits are designed to assist emergency response personnel in planning for catastrophic releases of chemicals. These limits are not developed to be used as safe limits for routine operations. The ERPG limits consist of three levels for use in emergency planning and are typically 1-hour values; 10-minute values have also been established for HF. For the 1-hour limits, the ERPG 1 (2 ppm) is based on odor perception and is below the concentration at which mild sensory irritation has been reported (3 ppm). ERPG 2 (20 ppm) is the most important guideline value set and is the concentration at which mitigating steps should be taken (such as evacuation, sheltering, donning masks). This level should not impede escape or cause irreversible health effects and is based mainly on the human irritation data in references 57 and 58. ERPG 3 (50 ppm) is based on animal data and is the maximum nonlethal level for nearly all individuals. This level could be lethal to some susceptible people. The 10-minute values established for HF and used in emergency planning in fires where HF vapor is generated are ERPG 3 = 170 ppm, ERPG 2 = 50 ppm, and ERPG 1 = 2 ppm.

3. ALTERNATIVE TECHNOLOGIES.

Nonhalocarbon substitutes are increasingly being considered as options to the use of halons. Already, water sprinklers are replacing halon systems in many applications. Dry chemical extinguishants and carbon dioxide (CO₂) are also receiving increased use. Alternatives can be divided into two types: classical alternatives and new alternatives (see table 14). Note that the word "new" does not necessarily imply that a technology was developed recently, but that there is a new or renewed interest in the use of a technology as a replacement for halons. Misting and particulate aerosols require decreased amounts of agent. This may decrease the probability of secondary fire damage. Thus, these technologies may allow protection while minimizing the problems normally associated with water and solids. Recent advances allow the use of inert gases and inert-gas blends in new applications, particularly in occupied areas.

TABLE 14. ALTERNATIVES

Classical	New
Foams	Water Misting
Water Sprinklers	Particulate Aerosols
Dry Chemicals	Inert Gases
Carbon Dioxide	Solid Propellant Gas Generators
Loaded Stream	Combination

3.1 FOAMS.

Foams are an alternative to halon systems for a number of hazards, particularly those involving flammable liquids [59]. Foams extinguish fires by establishing a barrier between the fuel and air. Drainage of water from the foam also provides a cooling effect, which is particularly important for flammable liquids with relatively low flash points and for Class A fuels where glowing embers are a problem. The disadvantages of foams are similar to those of water. They can cause secondary damage and cannot be used on fires involving electrical equipment without careful design considerations.

There are four basic classifications for foam fire protection systems:

- a. Fixed Foam Systems are complete installations with foam piped from a central location and discharged through fixed nozzles. The concept is similar to a fixed halon system; although the applicability is very different.
- b. Semifixed Foam Systems are of two types. In one type, the foam agent is connected to a fixed piping system remote from the fire threat at the time the foam is required. In the second type, foam is delivered from a central station to portable foam makers, which may include hose reels.
- c. Mobile systems are vehicle-mounted or vehicle-towed complete foam units.

- d. Portable systems are nothing more than hand-carried mobile systems. Portable foam extinguishers are generally intended for use on flammable liquids; although foam extinguishers may also be used for general protection against Class A fires in the same manner as water extinguishers.

3.1.1 Low-Expansion Foam.

Low-expansion foams have the following limitations:

- a. Low-expansion foams are suitable only for horizontal or 2-dimensional fires, not 3-dimensional.
- b. The correct foam must be used depending on the type of liquid fuel. There are two basic types of low-expansion foams: hydrocarbon fuel foams and polar solvent foams. The polar solvent foams are primarily for alcohol fires, but may also be used on hydrocarbon fires. These are sometimes called universal foams. Hydrocarbon fuel foams are usually lower cost, but the foam blanket degrades in the presence of polar chemicals like alcohols.
- c. Different kinds and brands of foam concentrates may be incompatible and should not be mixed during storage.
- d. Since low-expansion foams consist of at least 90 percent water, their use is limited to applications where unacceptable water damage or electrical conductivity is not a problem.
- e. Foams are generally used as concentrates, which are proportioned with water during delivery. The effectiveness of a foam on a fire is highly dependent on the system designed to proportion and deliver the foam.

3.1.2 High- and Medium-Expansion Foam.

High-expansion foam systems are uncommon but can be used for total flood of a protected space; particularly where a Class A fire may be difficult to access for manual firefighting. Examples of applications include areas between floors, in which a small number of high-expansion foam systems have recently been used in preference to using halon, and marine machinery spaces. A preliminary evaluation of high-expansion foams for U.S. Naval shipboard applications has been performed [60]. Disadvantages of high-expansion foam systems include greater weight and space requirements, the need for a suitable water supply, relatively long extinguishing time, and possible cleanup problems. Also, due to poor visibility, the use of high-expansion foams can be dangerous in large, cluttered, or hazardous enclosures where people might be present. Toxicity and asphyxiation are not considered to be problems with high-expansion foam, total-flood systems.

High- and medium-expansion foams have the following limitations:

- a. Since high- and medium-expansion foams have a relatively low water content, they are not as effective as low-expansion foams for most fire scenarios. The hazard must be carefully evaluated and the foam system carefully designed.
- b. The use of high- and medium-expansion foams for fires involving flammable liquids and gases must be carefully evaluated in view of the actual situations. These foams are not as forgiving of poor engineering design and application. In particular, high- and medium-expansion foams are often useless against fires involving liquefied natural gas.
- c. Although high- and medium-expansion foams contain less water than low-expansion foams, they should not be used with fires of water-reactive materials or on Class C fires without careful evaluation and testing.

3.2 WATER SPRINKLERS.

Water is a very effective extinguishing agent because of its unusually high specific heat and heat of vaporization. Water can be delivered in three ways—from fixed systems, from handlines, and from portable extinguishers. It is primarily a Class A fire extinguishant, cooling the fuel to a temperature below the fire point; however, fine water sprays can be very effective against Class B fires and have the additional benefit of cooling to prevent reignition. The quantity of water required is, in some installations, less than the amount of halon needed for the same degree of protection.

As an extinguishing agent, water has a number of disadvantages compared with halons:

- a. Secondary damage (damage to facilities and contents due to the agent) may result from discharge.
- b. A cleanup requirement may exist after discharge: runoff water may have to be removed and contents of protected areas may require drying.
- c. Water is unsuitable for discharge onto live electrical equipment.
- d. Water does not penetrate enclosures as well as halons and other gaseous agents.
- e. Discharge normally takes longer than that of a gaseous agent.
- f. Most water fire protection applications are unsuitable for Class B fires although this may be overcome by misting systems.
- g. Water causes problems with storage, discharge, and cleanup at very low temperatures.
- h. Of particular importance in aviation is that water may carry a relatively large weight penalty, though this may not be true for zoned systems.

There are several types of fixed water systems for fire protection [61]. Wet pipe sprinkler systems are widely used. These systems have pipes that are constantly pressurized with water and that are connected to sprinkler heads which are opened by heat activation. They require no electrically activated fire detectors. Dry pipe systems are filled with air or nitrogen under pressure. When the sprinkler heads are opened by fire, the gas is released allowing water to flow to the heads. These systems are a little more costly than wet pipe systems and have a slower response time. Preaction sprinkler systems require a detection system to actuate a valve allowing water to fill pipes to sprinkler heads which are closed until fire activation opens them. These systems are used primarily where inadvertent discharge must be avoided. A detector is required. Water deluge systems have heads that are normally open unlike the wet pipe, dry pipe, and preaction systems which require fire activation of the sprinkler heads. A detector activates a valve allowing water to discharge from all of the heads. This type of system results in widespread water discharge and, therefore, has a higher possibility of water damage. Deluge systems are unlikely to be used for replacement of Halon 1301 total-flood systems. Other, combination and special, systems have been used, including some that shut off the water when a fire has been extinguished.

Automatic sprinkler systems were first developed in the last century and are well proven, highly reliable form of fire protection. This is particularly true in general industrial and commercial premises in which none of the disadvantages listed above are of major practical significance. Automatic sprinklers may be used for protection of many facilities (e.g., computer rooms) for which halon is traditionally used. To avoid damage to the equipment, however, the electrical power must be deactivated before water is discharged. Although most of the new generation of computer equipment is not permanently damaged by water, if it is first powered down, it must be dried out before use. This means that either redundant equipment is needed or the facility must be able to withstand any losses due to down time.

A fixed water sprinkler system may be very cost-effective for protection of an area that already has halon systems if existing piping, valves, and miscellaneous equipment do not require major modifications. However, if protection of a limited area involves installation of a water supply and if a storage tank, pumps, and increased pipe sizing are required, sprinkler protection could be much more expensive than a halon system. Predesign inspections should be a mandatory consideration for all existing halon-protected areas.

3.3 DRY CHEMICALS.

Certain finely ground powders can be used as extinguishing agents. The extinguishing mechanism is complex and not fully understood. However, the mechanism depends mainly on the presence of a chemically active surface within the reaction zone of the fire. Sodium bicarbonate was one of the first dry chemical extinguishants to be used. Potassium bicarbonate and monoammonium phosphate were developed later in the 1960s. These powders typically have particle sizes of less than 10 μm up to 75 μm with average particle sizes of 20 to 25 μm .

Dry chemicals generally provide very rapid knockdown of flames and are more effective than halons in most applications [62]. The main disadvantages of dry chemical fire extinguishants include:

- a. poor penetration behind obstacles,
- b. no inhibiting atmosphere after discharge,
- c. no direct cooling of surfaces or fuel,^b
- d. secondary damage to electronic, electromechanical, and mechanical equipment,
- e. cleanup problems, and
- f. temporary loss of visibility if discharged in a confined space.

Fixed dry chemical systems are very uncommon; uses are normally limited to localized applications, such as with textile machines or deep-fat fryers, for which halons would not normally be used. However, these systems should be considered for fire suppression in some marine engine spaces and land-based transportation engine compartments.

Dry chemical extinguishers are suitable for Class A, B, and in some cases, C fires depending on the type of powder used. Powder extinguishers are often suitable substitutes for halon with fires of flammable liquids. They are also suitable for situations where a range of different fires can be experienced, e.g., electrical fires, flammable liquid fires, and fires in solids. In this respect, powder extinguishers resemble halon extinguishers.

3.3.1 Monoammonium Phosphate.

This is an excellent explosion and fire suppressant and is effective on Class A, B, and C fires. It is, however, corrosive on metals. This material is often referred to as "ABC Powder."

3.3.2 Sodium Bicarbonate.

This, along with monoammonium phosphate, is considered to be an excellent explosion suppressant. It has been used in stove-top fire extinguishers. It is the largest selling dry chemical primarily because of its low cost and its use in training.

3.3.3 Potassium Bicarbonate.

Potassium bicarbonate is a widely used dry chemical fire extinguishant. There is some indication that the potassium ion has a chemical effect on fires. It is widely recognized that the amount of carbon dioxide released by this agent, and by sodium bicarbonate, in fires is insufficient to explain the fire suppression ability.

^b Cooling of the flame due to thermal decomposition has been proposed as a mechanism for flame suppression by dry chemical agents (Ewing, C. T., Hughes, J. T., and Carhart, H. W., "The Extinction of Hydrocarbon Flames Based on the Heat-Absorption Processes Which Occur in Them," *Fire and Materials*, Vol. 8, No. 3, pp. 148-156, 1984). However, this is somewhat different from the direct cooling of surfaces, fuel, and flames by an agent such as water where cooling occurs in the absence of flame/agent interaction.

3.3.4 Proprietary.

Here, the term proprietary is used to denote a special dry chemical rather than one of those described above which have small amounts of an additive to improve flow and other characteristics. Monnex, a urea potassium carbonate developed by ICI, is an exceedingly effective proprietary dry chemical. However, it is more expensive than the generic agents discussed above and has a somewhat less effective delivery.

3.4 CARBON DIOXIDE.

Carbon dioxide (CO₂) resembles the other inert gases discussed in section 3.8. However, CO₂ can be considered a classical alternative and is the most common inert gas used as a fire extinguishant today. The physiological effects of carbon dioxide, however, differ significantly from those of the other inert gases. Like Halons 1301 and 1211, CO₂ is a gas at normal ambient temperature and pressure. It is also a clean, electrically nonconductive agent with good penetrating capability. Carbon dioxide is discharged as a gas, though some frozen particulate (dry ice) often forms. The presence of frozen particulate increases the heat absorption capacity. Only through the use of refrigerated systems (see below) can any liquid discharge occur.

At one time, CO₂ systems were used for many of the applications that now use halon. Indeed, fixed CO₂ systems still remain in popular use for a number of applications, particularly in unmanned areas. Carbon dioxide is also a common agent in portable fire extinguishers and in localized fixed systems. Research is under way for using carbon dioxide as a component in twin-fluid water misting systems (section 3.6) and mixed with particulate aerosols (section 3.7). Carbon dioxide is used as a pressurizing agent in some dry chemical extinguishers.

Design concentrations for carbon dioxide total-flood systems for protection against Class B fires involving typical liquid hydrocarbons range from 34 to 43 percent depending on the fuel [63] compared with approximately 5 to 8 percent for Halon 1301 systems [42]. Cup burner data show that a concentration of approximately seven times that of halon is required for *n*-heptane [64]. (Note, however, that this does not imply that seven times as much CO₂ is needed in a streaming or localized application.) Carbon dioxide is less efficient than halons—the time to extinguishment is longer and, in general, storage requirements are greater. Carbon dioxide is, however, more efficient than other inert gases, a characteristic that may be due to endothermic decomposition processes. For most total-flood applications, an agent storage volume of approximately eight times that required for halon is required for most CO₂ systems (however, see the next paragraph for a discussion on liquid CO₂ systems where the ratio can be as low as four times). Weight and space considerations are more relevant in retrofitting than in new installations, but they are unlikely to be major obstacles for retrofit into existing industrial and commercial facilities. On the other hand, weight and space requirements are likely to be a barrier for CO₂ retrofit of onboard aircraft applications. Traditionally, CO₂ fixed systems cost two to three times (excluding agent cost) that of halon systems.

Pyrozone Sales Pty. Ltd. in Australia manufactures a range of modular low-pressure CO₂ storage units that use liquid CO₂. Liquid CO₂ requires considerably less volume than the gas phase agent found in most CO₂ systems and, moreover, it is claimed that Pyrozone Systems have the potential

to use existing Halon 1301 pipework and detection equipment. The Pyrozone units use refrigeration to maintain the CO₂ as a liquid and have integral contents measuring capability. Pyrozone units are designed to be refilled in situ negating the need to dismantle any part of the system after a discharge.

Concerns exist about the safety hazard to personnel in areas protected with fixed, total-flood CO₂ systems. Unlike the other inert gases, CO₂ is toxic in large amounts (it is a respiratory regulator), and the design concentrations are well above dangerous levels (above 9 percent, loss of consciousness occurs within a short time, with death occurring around 25 to 30 percent [65]). With most fixed localized systems, on the other hand, the hazard is much less and with portable extinguishers, any hazard is minimal. It is possible to manage the safety hazard with fixed, total-flood CO₂ installations by designing the system to ensure that automatic discharge does not occur while people are present in the protected area or by using manual activation. There are many well developed internationally recognized standards that provide the guidelines for the safe use of CO₂ total-flood systems. However, owing to the toxicity and the reduced efficiency, CO₂ is generally less attractive to fire insurers.

Concerns have been expressed about erasing of magnetic tape and damage from thermal shock due to CO₂. Testing has failed to substantiate the first concern, and thermal shock does not normally occur unless the discharge is directed at objects close to the nozzle. Some specialized installations are designed to pass the CO₂ through a vaporizing unit (converting all of the CO₂ to a gas) to reduce cooling by vaporization and sublimation. Continued use by telecommunications and modern power supply industries support compatibility of CO₂ with risks of this type.

Carbon dioxide portable fire extinguishers have been available for many years and are in common use. They have certain disadvantages compared with Halon 1211: larger size, greater weight, lower efficiency, shorter throw range, and no Class A rating. In many applications, however, these disadvantages do not rule out the use of CO₂ fire extinguishers. Note, however, that complete protection of any facility with CO₂ may leave the facility devoid of sufficient Class A protection, and other types of agents—water, foam, dry chemical—may be needed.

3.5 LOADED STREAM.

The term "loaded stream" is used to indicate any mixture of a salt (usually an acetate, a citrate, and/or a carbonate) with water. Most loaded stream agents are used for protection of cooking and restaurant facilities. Kidde puts out two different types of loaded water extinguishers with sodium acetate, water, and ethylene glycol—one contains a mixture with 50 percent sodium acetate and the other a mixture with 30 percent sodium acetate.

Recent work shows that sprays of aqueous solutions containing 60 percent potassium lactate or 60 percent potassium acetate are far superior to neat water sprays in extinguishing JP-8 fuel fires [66].^c The improved performance is attributed to the release of solid salts upon evaporation of

^c JP-8 is a hydrocarbon fuel with a flashpoint typically about 50°C. The fuel in the study cited here had a flashpoint of 50°C.

the water droplets. The work also shows that iodide salt solutions are superior to bromide salt solutions.

3.6 WATER MISTING SYSTEMS.

Water misting systems allow the use of fine water sprays to provide fire protection with reduced water requirements and reduced secondary damage. Calculations indicate that on a weight basis, water could provide fire extinguishment capabilities better than those of halons provided that complete or near-complete evaporation of water is achieved. Since small droplets evaporate significantly faster than large droplets, the small droplets achievable through misting systems could approach this capability. The NFPA 750 Standard on water misting systems [67] establishes 1000 microns (micrometers, μm) or less as being the water droplet size for a system to be designated as a water misting system; however, many misting systems have droplet sizes well below this value. Water misting systems extinguish fires by three mechanisms: (1) heat absorption through evaporation and, to a lesser extent, vapor-phase heat capacity, (2) oxygen dilution by the water vapor formed on evaporation, and (3) radiative heat obstruction by the mist.

A detailed review of water misting has been written by the Navy Technology Center for Safety and Survivability and Hughes Associates [68]. More recent reviews are presented in references 69 and 70. Water misting is being evaluated both as a possible replacement for total-flooding Halon 1301 systems [71] and for use in hand-held extinguishers [72].

At the request of the EPA, manufacturers of water misting systems and other industry partners convened a medical panel to address questions concerning the potential physiological effects of inhaling very small water droplets in fire and nonfire scenarios. Disciplines represented on the medical panel included inhalation toxicology, pulmonary medicine, physiology, aerosol physics, fire toxicity, smoke dynamics, and chemistry with members coming from the commercial, university, and military sectors. The executive summary of the final report [73] states the following:

"The overall conclusion of the Health Panel's review is that water mist systems using pure water do not present a toxicological or physiological hazard and are safe for use in occupied areas. The Panel does not believe that additional studies are necessary to reach this conclusion. The Health Panel recommends that additives be evaluated on a case-by-case basis depending on the toxic properties of the additive and the concentration at which it is used."

As a result of this study, the EPA is listing water mist systems composed of potable water and natural sea water as acceptable without restriction under SNAP. Water mist systems comprised of mixtures in solution must, however, be submitted to EPA for review on a case-by-case basis.

There are two basic types of water mist suppression systems—single fluid and twin fluid. Single-fluid systems utilize water stored or pumped under pressure; twin-fluid systems use air, nitrogen, or another gas to atomize water at a nozzle. The systems can also be classified according to the pressure in the distribution system piping as high pressure (above 500 psia (34.5 bar)), intermediate pressure (175 to 500 psia (12.1 to 34.5 bar)), and low pressure (175 psia (12.1 bar) or less). Both single- and twin-fluid systems have been shown to be promising for fire

suppression. Single-fluid systems have lower space and weight requirements, reduced piping requirements, and easier system design and installation; twin-fluid systems require lower water supply pressure, larger nozzle orifices (greater tolerance to dirt and contaminants and may allow the use of higher viscosity antifreeze mixtures), and increased control of drop size [68].

The performance of a water mist system depends on the ability to generate small droplet sizes and the ability to distribute mist throughout a compartment in concentrations that are effective [68]. Suppression effectiveness depends on five factors: (1) droplet size, (2) droplet velocity, (3) spray pattern, (4) momentum and mixing characteristics of the spray, and (5) geometry and other characteristics of the protected area.

Water mist systems are reasonably weight efficient. The use of small-diameter distribution tubing and the possible use of composite, lightweight, high-pressure storage cylinders would increase this efficiency. It may also be possible to integrate a central storage of water for use in several potential fire locations (for example, cargo and passenger cabin locations). This integration may not always be beneficial. It could introduce failure modes, decrease availability, and reduce safety.

The major difficulties with water mist systems are those associated with design and engineering. These problems arise from the need to generate, distribute, and maintain an adequate concentration of the proper size drops throughout a compartment while gravity and agent deposition loss on surfaces deplete the concentration. Water mist systems have problems extinguishing fires located high in a space away from the discharge nozzles. Water mists also have difficulty extinguishing deep-seated Class A fires. Other concerns that need to be addressed are (1) collateral damage due to water deposition, (2) electrical conductivity of the mist, (3) inhalation of products of combustion due to lowering and cooling of the smoke layer and adhesion of the smoke particles to the water drops, (4) egress concerns due to loss of visibility during system activation, (5) lack of third-party approvals for most or all applications, and (6) lack of design standards [74]. Concern has also been expressed about the possibility of clogging of small nozzle orifices used in some systems.

For aircraft use, misting systems are most appropriately considered for cargo bays and, possibly, engine nacelles. Some concern has been expressed that water mists may be inappropriate for cargo bays due to the possibility of deep-seated and hidden fires. The FAA William J. Hughes Technical Center data show that deep-seated fires are probable and have caused several fatal cargo compartment fires. Tests by the FAA and others on deep-seated cargo fires indicate that water mist systems can be effective in combating such fires. Water mist may hold several advantages and should be considered for cargo bay application.

The use of water mists for protection of nacelles may be difficult. First, the low temperatures, around -57°C (-70°F) at altitudes of 36,000 feet, hinder storage, discharge, and evaporation. Second, there is concern about the possible collateral damage due to thermal shock when water contacts hot titanium components. Third, water systems are likely to be bulky. Finally, water is not expected to be distributed as uniformly as halocarbon and other gaseous agents.

Table 15 gives a list of manufacturers for water misting systems. Only the country for the main headquarters is listed; however, most have locations in several countries.

TABLE 15. COMMERCIAL WATER MISTING SYSTEMS

Manufacturer or Distributor	Trade Name	Pressure
Single Fluid		
Baumac International, USA	MicroMist	High
Chemetron Fire Systems, USA	Chemetron	Low
Fike Corporation, USA	Micromist	Medium
FOGTEC Fire Protection, Germany	FOGTEC	High
Ginge-Kerr, Denmark/Kidde-Deugra, Germany	AquaSafe	Low
Grinnell, USA	AquaMist	Medium
GW Sprinkler, Denmark		Low/Medium
Marioff Oy, Finland	Hi-fog	High
Phirex, Australia	^a Mistex	Low/Medium
Semco Maritime A/S, Denmark	Sem-Safe	High
^b Spraying Systems Company, USA	FogJet	High
Total Walther, Germany	MicroDrop	Low
Ultra Fog AB, Sweden	Ultra Fog	High
Twin Fluid		
Securiplex, Canada	Fire Scope 2000	Low
International Aero Inc., USA	IAI Water Mist	Low
Technology Unknown		
DAR CHEM, UK		

^a Both fixed and self-contained portable systems.

^b Manufactures nozzles only.

3.7 FINE PARTICULATE AEROSOLS.

Fine particulate aerosols are air-suspended dry chemicals with micron-size particles that give some total-flood capabilities. Dry chemical agents are at least as effective as halons in suppressing fires and explosions in many applications; however, such agents can damage electronic and mechanical equipment. Moreover, dry chemical agents, as now used, do not provide explosion inertion or fire suppression for time periods similar to those provided by halon systems due to settling of the particles. The discharge of dry chemicals also obscures vision. In Geneva, Switzerland, at the 2nd Conference on the Fire Protecting Halons and the Environment, 1-3 October 1990, representatives of the Soviet Union provided information on a solid agent that they claimed provided relatively long-term (20 minutes or more) inertion of an enclosed volume and excellent fire extinguishment [75]. The first detailed technical information on this technology, however, was provided in the 1993 Halon Alternatives Technical Working Conference in Albuquerque, New Mexico [76-78].

Most, but not all, of the commercialized technologies for production of particulate aerosols employ an oxidizing agent and a solid fuel which, when ignited, produces a fine solid particulate aerosol providing extinguishment similar to that provided by dry chemical agents. An alternative process manufactures aerosol-size dry chemical agents by spray drying—spraying aqueous solutions into a heated space [79]. The small particle size appears to increase efficiency, decrease deposits, and increases the space-filling capability (multidimensionality) relative to normal dry chemical agents. Some have termed this type of technology “pyrotechnically generated aerosol (PGA).” Others have suggested that the term “pyrogenic aerosol” is more appropriate. In this report, “pyrotechnically generated aerosol” and “pyrogenic aerosol” are considered synonymous. PGAs are generated from nonpressurized containers. For a review of this area see reference 80.

As particle size decreases, the particulate surface on which heterogeneous recombination of combustion chain propagators can occur increases (e.g., Reactions 1, 2).^d Moreover, as particulate size decreases, the sublimation rate increases, enhancing homogenous gas phase inhibition mechanisms, examples of which are shown in Reactions 3 through 5 for potassium-containing aerosols (the most common type) [81]. Thus, in addition to improving dispersion, the small particle sizes inherent in particulate aerosols give these materials a greater weight effectiveness than standard dry chemical agents, decreasing problems due to residue. Both heterogeneous (particulate surface) and homogenous (gas-phase) inhibition appear to contribute to flame inhibition by particulate aerosols. Heat absorption by decomposition reactions and phase changes may also contribute.



The following presents information on some commercialized materials. The design factor is the mass of unignited material per unit volume of a protected area as specified by the manufacturer or distributor. At present, the NFPA has no standard on fine aerosol technology.

3.7.1 Spectrex Fire-Extinguishing Agent.

The family of Spectrex fire-extinguishing agents (S.F.E.) (also known as EMAA, Encapsulated Micron Aerosol Agent) [77] are contained in generators and in applicators. Ansul is licensed by Spectrex Inc. of New Jersey, USA, to produce the S.F.E. agents under the trade name Micro-K and to market them worldwide. The powdered aerosol agents are produced in an oxidation-reduction combustion process that takes place in a combustion chamber specifically designed to contain various amounts of solid-casted material from 100 grams and up to several kilograms.

^d Here, “•” denotes a free radical.

The combustion chamber is introduced in modular units (generators) that include a cooling means (chemical and physical) as well as discharge outlets that direct the aerosol flow towards the protected volume. The agents provide an air-suspended dry chemical aerosol with micron-size particles that give total-flood capabilities [82].

U.S. Navy and U.S. Air Force tests and evaluation programs [80] indicate that on a weight basis, the agents are three times more efficient than regular dry powders and five times more efficient than halocarbon extinguishing agents. The agents, designated as "powdered aerosol A," have been approved under SNAP for total flooding of unoccupied areas [9]. Approval is pending for occupied areas [11 and 12].

The S.F.E. agents were also evaluated by the FAA in a test program performed at its test facilities at the William J. Hughes Technical Center. S.F.E. Formulation "D" performance is reported in reference 83 and further in section 4.4.3 of this report.

Before ignition, S.F.E. has a density of 1300 to 1800 kg/m³. The combustion temperature is 1500 to 2400 K, and the combustion velocity is 0.3 to 1.5 mm/sec. The material, which may be a solid pellet or a gelled paste, has a shelf life of 15 years. Prior to combustion, the S.F.E. solid material is not affected by prolonged exposures to extreme temperatures (from -55°C to +250°C) and remains functional in its original state (does not change phases to liquid or gas). Emissions from S.F.E. contain 40 percent particulate aerosols with a median diameter of 1 to 2 micron [84], comprising salts such as K₂O, KCl, and K₂CO₃. The remaining 60 percent of the emissions are gaseous combustion products such as CO₂, N₂, H₂O, O₂, and traces (ppm) of hydrocarbons. Hazardous gases such as CO and NO_x are not observed in improved formulations recently tested.

The toxicity of S.F.E. agents has been evaluated by the U.S. Navy Medical Research Institute Toxicology Detachment [85-89]. Two formulations, A1 and A2, were compared. Prolonged exposure of test rats to powdered aerosol S.F.E. formulation A1 at concentrations exceeding 80 g/m³ caused toxic effects that resulted in deaths and have led to the development of formulation A2. Multiple exposures to the byproducts of pyrolyzed formulation A2 at concentrations ranging from 50 g/m³ to 240 gr/m³ caused no deaths to Fischer 344 rats and only minimal toxic effects [87]. All the animals recuperated after the exposure ceased. Formulation A2 is commercialized as S.F.E.

The S.F.E. agents are casted solids contained in modular units (generators) of various sizes containing from 100 grams to 5 kilograms net weight S.F.E., some of which include cooling. The approximate design factor is 50 g/m³ for direct material activation in enclosed areas and 100 to 120 g/m³ when discharged from cooled generators, where a safety factor of 20 percent is included [90]. Typical system configurations include several modular units connected in a loop to a control box/display panel activated electrically by a signal from a separate detection system or by a self-contained detection element incorporated in the modular unit. The modular units and systems are manufactured and distributed by Spectrex (USA), Grinnell Ansul (USA), Gamesa - I.S.E. (Spain), and other companies. The main applications/installations are Modular Unit Micro-K for electrical board, engine compartments, etc., by Ansul; nuclear power stations and transformer rooms by Gamesa - I.S.E.; and deployable and portable extinguisher by Spectronix Ltd., Israel.

3.7.2 PyroGen and Firepak.

A pyrotechnically generated aerosol manufactured by Pyrogen Corporation has been approved under SNAP as Powdered Aerosol C for total flood of normally unoccupied areas [11 and 12]. The agent is marketed in the U.S. by International Aero Inc. under the name Firepak and in most other countries, including Australia, New Zealand, Southeast Asia, and Europe by Pyrogen Corporation under the trade name PyroGen^c.

The self-contained nonpressurized canister contains two solid tablets—an aerosol-producing propellant and a coolant. Upon activation of the canister, either electrical or thermal, the propellant burns to produce a fire-extinguishing aerosol—a mixture of micron-sized chemical powders and inert gases. The aerosol propels itself through the coolant and out of the canister into the enclosure.

The aerosol-producing propellant consists mainly of potassium nitrate and plasticized nitrocellulose. Combustion products of the propellant are finely dispersed potassium carbonates, carbon dioxide gas (1.2 percent), nitrogen gas, and water vapor; the mixture being the actual extinguishing medium. The design concentration—the mass of nonignited solid aerosol-producing propellant required to produce an adequate amount of aerosol to extinguish a specified type of fire per unit of volume—has been established as 100 g/m³ for Class B fires and surface Class A fires.

Like other PGAs, the use of Firepak in the United States is now limited to normally unoccupied areas, in part because the finely dispersed solid particles of the aerosol decrease visibility in the protected enclosure. Some byproducts of the aerosol generating reaction of the solid propellant (e.g., carbon monoxide and nitrogen oxides) could cause moderate local irritation of the upper respiratory tract and eyes. Elevated temperature of the aerosol at the discharge outlet requires that minimum clearances be observed.

3.7.3 Soyus.

Dynamit Nobel GmbH Explosivstoff und Systemtechnik, Troisdorf, Germany, produces a number of different sizes of pyrotechnically generated aerosol fire-extinguishing generators. The aerosol generating units, which are marketed under the trade name Soyus, contain an ignition device, the fire-extinguishing composition, a reaction compartment, and a cooling unit in a cylindrical metal housing. The generators produce potassium carbonate, K₂CO₃, of which 99 percent has a particle size of 0.5 to 4 micron. The SO 200 E-E01 unit (height = 118 mm, diameter = 82 mm, weight = 0.88 kg) protects a volume of approximately 2.0 m³. The SO 300 E-E01 unit (height = 208 mm, diameter = 82 mm, weight = 1.49 kg) protects a volume of approximately 3.0 m³. Aerosol generation is reported to last 8 seconds for the first unit and 10 seconds for the second unit with a particulate residence time of approximately 1 hour. Ignition can either be electrical or manual.

^c This agent was originally marketed as FEAS by Bytenet Holdings, Australia.

3.7.4 Aero-K.

FireCombat produces three PGA generators (trade name Aero-K), which protect volumes of 1.0, 2.5, and 20 m³ and contain charges of 0.1, 0.250, and 1.65 kg. The generator weights are 0.34, 0.96, and 5.50 kg. The charges consist of alkaline metal nitrates and a combustible organic binder. The combustion products are primarily potassium salts with some ammonium bicarbonate. The aerosol concentration required to extinguish a fire is 40 to 80 g/m³.

3.7.5 KD-A 96.

Kidde-Deugra produces a very fine aerosol powder (KD-A 96) using a dry spray technique [79]. The aerosol powder is stored in cylinders together with inert gases as the propellant. This procedure avoids problems of hot gas emissions found for PGAs.

3.8 INERT GASES.

Combustion cannot occur when the oxygen content of air at normal pressures is sufficiently reduced (below approximately 15 percent fires cannot be initiated; at lower concentrations, fires are extinguished). Thus, inert gases, such as nitrogen and argon, etc., can extinguish fires by diluting the air and decreasing oxygen content. Extinguishment is also facilitated by heat absorption.

Health problems can occur at low concentrations of oxygen. Although asphyxiation is not probable at concentrations required to extinguish a fire, sufficient impairment could occur to prevent safe evacuation or emergency response. OSHA requires that no one enter a space with less than 19.5 percent oxygen without a self-contained breathing apparatus (SCBA). NIOSH gives the following effects at varying oxygen concentrations [91]. Note, however, that health problems that can occur would not happen immediately and would be a problem only for extended stays in an environment with a low oxygen level. Thus, there is some feeling that these predictions are meaningless without specifying a time period [92].

- 16 percent—impaired judgment and breathing
- 14 percent—faulty judgment and rapid fatigue
- 6 percent—difficult breathing, death in minutes

The minimum oxygen concentration where astronauts can still perform the minimum physical and mental activities required to safely pilot a spacecraft, although with great difficulty, has been established by the National Aeronautics and Space Administration (NASA) as 12.3 volume percent [93]. Between 16 and 12.3 volume percent oxygen, performance is increasingly impaired. An expert panel has reported, however, that a 3-minute exposure to an atmosphere containing 10 volume percent oxygen provides an adequate margin of safety considering the variability of a working population, but that lethality occurs quickly at oxygen concentrations below 8 volume percent [94].

One method that can be used is to increase the atmospheric pressure so that the partial pressure of oxygen does not decrease below that required for human respiration while reducing the percent

oxygen to the point that extinguishment occurs [95]. The higher heat capacity due to increased atmospheric pressure also helps suppress fires. For example, submarines could use nitrogen flooding to dilute the oxygen while keeping its partial pressure constant to maintain life support [96]. This method can only be applied to completely enclosed areas with high structural strengths and is, therefore, limited to very few applications.

Pure and blended inert gases marketed as alternatives to halons are shown in table 16. All of the agents shown in this table are acceptable or proposed acceptable under SNAP. The concentrations needed for extinguishment are approximately 34 to 52 percent, depending on the fuel and the fire scenario. The extinguishing properties of argon are similar to those of nitrogen for Class A, B, and C fires; however, unlike nitrogen, argon is suitable for Class D fires involving metals that react with nitrogen (e.g., magnesium and lithium). Effective extinguishment of a series of *n*-heptane, wood crib, and polyvinyl chloride (PVC) cable crib fires has been reported by the UK Loss Prevention Council for IG-541, IG-55, and IG-01 using the recommended design concentration and systems provided by commercial equipment manufacturers [47]. In general, extinguishment times were longer with the inert gases than found for halocarbon extinguishing agents.

TABLE 16. INERT GASES

Designation	Composition	Extinguishment Concentration ^a (vol %)	Manufacturer
IG-541	Nitrogen 52 ±4% Argon 40 ±4% CO ₂ 8 ±1%	33	Ansul Incorporated, USA, and Fire Eater A/S, Denmark (INERGEN)
IG-55	Nitrogen 50 ±5% Argon 50 ±5%	35	Ginge-Kerr Denmark A/S (ARGONITE)
IG-01	100% Argon	42	Minimax GmbH (Argotec)
IG-100	100% Nitrogen	33	Koatsu (NN100), Japan

^a Cup-Burner Extinguishment Concentration with *n*-heptane fuel [97].

NOAEL and LOAEL values, which are normally based on cardiac sensitization for halocarbons, are inappropriate for inert gases. The EPA allows design concentrations to an oxygen level of 10 percent (52-percent agent) if egress can occur within 1 minute, but to an oxygen level of no lower than 12 percent (43-percent agent) if egress requires more than 1 minute [11 and 12]. Designs to oxygen levels of less than 10 percent are allowed only in normally unoccupied areas and only if personnel who could possibly be exposed can egress in less than 30 seconds.

In place of NOAEL and LOAEL values, the 2000 NFPA 2001 Standard [21] uses a no effect level (NEL) and a low effect level (LEL) for inert gases. These values are based on physiological effects in humans in hypoxic atmospheres and are the functional equivalents of the NOAEL and

LOAEL values given for halocarbons. All inert gas agents listed in the 2000 Standard (IG-01, IG-541, and IG-55) have sea level-equivalent^f NEL and LEL values of 43 percent (12-percent oxygen) and 52 percent (10-percent oxygen), respectively. Similar to that done for halocarbon agents, the Standard allows the use of an inert gas agent up to the LEL value for Class B hazards in normally occupied areas where a predischARGE alarm and time delay are provided. In the absence of a time delay, only design concentrations up to the NEL are allowed. One major difference between the NFPA and EPA approaches is that the allowable design concentrations are not based on specific egress times in the NFPA Standard.

NEAG/HAG recommends [28] that oxygen concentrations in occupied areas protected by inert gas systems not be less than 12 percent unless a room can be evacuated in 1 minute (2 minutes in the case of INERGEN). This oxygen level corresponds to an inert gas concentration of 43 percent. NEAG/HAG also recommends that exposures to oxygen levels less than 10 percent not be allowed for any period of time.

3.9 SOLID PROPELLANT GAS GENERATORS.

Gas generator technology uses ignition of solid propellants to generate large quantities of gases. This gaseous effluent can either be used as is to create an inert environment or can be enhanced with various active agents to more aggressively attack the fire. The U.S. Navy has conducted numerous feasibility and design verification tests on several aircraft platforms to assess and refine solid propellant gas generator (SPGG) designs. NAVAIR has qualified, installed, and has several years of flight experience with SPGG technology aboard their F/A-18E/F and V-22 aircraft, with notable success in already having successfully extinguished an in-service 3-D pressurized fuel-fed fire in a V-22 mid-wing area. Currently, there is serious consideration by NAVAIR Program Managers to evaluate chemically active gas generators as a means of enhancing system performance/efficiency even further. The U.S. Air Force has been evaluating the technology for aircraft dry-bay applications and will be testing SPGGs for protection of F-22 aircraft. The U.S. Army TACOM (Tank Automotive Command) has been performing testing in engine compartments of tracked vehicles and may also evaluate SPGG technology in crew compartments. Several overviews of SPGG technology and the progress of testing conducted to date have been presented [98-100].

3.9.1 Primex Aerospace Inert Gas/Powdered Aerosol Blend.

Primex Aerospace Company, which has been supporting U.S. Department of Defense (DoD) testing, has announced that initial engineering, manufacturing, and development contracts have been received from two airframe manufacturers to protect aircraft dry bays [101]. The Primex Aerospace device uses an electrically activated squib to ignite a solid propellant that generates an inert mixture of nitrogen, carbon dioxide, and water vapor.

^f The term "sea level-equivalent" means concentrations that have the same oxygen partial pressures as those given by the NEL and LEL values at sea level (respectively, 91.2 Torr and 76 Torr partial pressures at an ambient total pressure of 760 Torr). For example, at an ambient total pressure of 600 Torr, the oxygen concentrations would have to be 15.2% and 12.7% to achieve the same oxygen partial pressures. This would correspond to allowable agent concentrations of 27.6% and 39.5%.

Primex Aerospace markets FS 0140, which has been approved under SNAP as Inert Gas/Powdered Aerosol Blend for use as a total-flood agent in unoccupied areas [12].

3.9.2 Walter Kidde Aerospace/Atlantic Research Corporation Consortium.

Walter Kidde Aerospace has teamed with Atlantic Research Corporation to develop gas generator technology for aviation and defense applications. The Walter Kidde Aerospace/Atlantic Research Corporation Consortium is being funded by the DoD under a Defense Advanced Research Projects Agency (DARPA) "Technology Reinvestment Program." This program will develop gas generator/vaporizing liquid agent hybrid extinguishers and gas generators that expel chemically active flame inhibiting species for the F-22 dry bay and other military applications. The chemically active gas generators have been shown to be more efficient on a weight basis than inert gas generators [102]. In addition, the Walter Kidde Aerospace/Atlantic Research Corporation Consortium is being funded by Battelle Labs to provide chemically active gas generator hardware for the F-22 engine nacelle fire protection test program.

3.10 COMBINATION AND NEW FOAM AGENTS.

Mixtures with water or with halocarbon bases have been marketed for many years. One example is the loaded stream type of agents mentioned earlier. In addition, blends of dry chemicals with halons or other halocarbons, sometimes with a gelling agent, have been marketed. With the phaseout of halons, there is an increased interest in and development of such mixtures.

3.10.1 Envirogel.

The SNAP list gives a variety of formulations under the category "gelled halocarbon/dry chemical suspension" (designated as "Powdered Aerosol B" in the first SNAP listing [9]) developed for particular markets. The materials, which are marketed under the trade name Envirogel by Powsus Inc., have been tested in a number of applications, including tracked vehicles [103 and 104]. Testing to date indicates that at least some formulations have an effectiveness similar to that of Halon 1301 on either a weight basis or a storage volume basis [105]. Each blend contains one or more halocarbons, a dry chemical, and a gel that keeps the powder and gas uniform.

The gelled agents are acceptable under SNAP for use in a streaming application provided that any halocarbon contained has a cardiac sensitization LOAEL of at least 2.0 percent and that the dry chemical is one that is now widely used (i.e., monoammonium phosphate, potassium bicarbonate, and sodium bicarbonate) or is ammonium polyphosphate [12]. Among the halocarbons included in the SNAP submission were HFC-227ea, HFC-125, HFC-134a, and HFC-125 blended with HFC-134a. Also judged acceptable under SNAP for use as total-flood agents in normally unoccupied areas are formulations containing ammonium polyphosphate and monoammonium phosphate blended with either HFC-125 or HFC-134a [11 and 12].

3.10.2 Cease Fire.

Cease Fire manufactures CF-33, a patented blend of monoammonium phosphate and a polymer that absorbs an extinguishing gas. The automatic overhead Cease Fire units are UL listed for Class A, B, and C fires and are available in four sizes with coverage from 800 to 2700 cubic feet.

3.10.3 FlameOut.

FlameOut, manufactured by Biogenesis Enterprises solely for Summit Environmental Corporation, Inc., is acceptable as a Halon 1211 substitute under SNAP with the generic name Surfactant Blend A [9]. The material is a mixture of organic surfactants and water, which is diluted to strengths of 1 to 10 percent in water for use. The surfactants, like all wetting agents, may enhance the rate of heat absorption by water. The blend acts on oil, gasoline, and petroleum-based liquid fires (Class B) by encapsulating the fuel, thus removing the fuel source from the fire. This feature prevents flame propagation and reduces the possibility of reignition. It can also be used on Class A fires. The agent is UL listed as a wetting agent in addition to water for extinguishing Class A and B fires. The extinguishant is a blend of complex alcohols, lipids, and proteins. FlameOut was originally approved by the U.S. EPA SNAP program as a replacement for Halon 1211, under the trade name ColdFire 302. This product should not be confused with ColdFire as manufactured by FireFreeze Worldwide. It is an entirely different blend. Summit Environmental Corporation owns the patent and intellectual property rights to ColdFire 302/FlameOut.

3.10.4 ColdFire.

FireFreeze Worldwide, Inc. manufactures ColdFire, a proprietary blend of organic surfactants and water, which is diluted to strengths of 1-10 percent in water. The surfactants in ColdFire, like all wetting agents, may increase heat absorption by water. ColdFire is UL listed as a wetting agent for Class A and B fires. The agent is said to extinguish Class B fires by fuel encapsulation to separate fuel from fire, reducing possible reignition and preventing flame propagation. ColdFire has successfully completed preliminary testing on molten magnesium and titanium fires (Class D) with Underwriters Laboratories of Canada. ColdFire should not be confused with ColdFire 302/FlameOut. It is an entirely different blend.

3.10.5 Fire-X-Plus.

Fire-X-Plus, a foam produced by Firefox Industries, is acceptable under SNAP as a Halon 1301 replacement with the generic name Foam A (formerly Water Mist/Surfactant Blend A) [12].

4. APPLICABILITY OF TECHNOLOGIES TO AIRCRAFT APPLICATIONS.

As noted in the introduction, a major goal for the Task Group on Halon Options is an assessment of the applicability of halon substitute technologies to each major area of onboard aircraft use: (1) engine nacelles and APU (auxiliary power unit) compartment, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection.

In evaluating agents for recommendations, we considered the essential properties/characteristics, the likely fire threat, the present fire detection and suppression practices, applicable regulations, and the current state of the technology. We did not allow the requirements of existing systems to influence our analysis. To allow this would have forced us to just one recommendation: Halon 1301 for total-flood applications and Halon 1211 for streaming agent applications.

4.1 REQUIREMENTS.

The candidate agents must meet the following requirements. The requirements imposed by the specific threat or application are additional to these requirements. A discussion of requirements or possible requirements by application has been published by the FAA [106].

- a. The agent must be suitable for the likely Class of fire. It should be recognized by a technical, listing, or approval organization—National Fire Protection Association (NFPA), Underwriters Laboratories (UL), Factory Mutual Research Corporation (FMRC), etc.—as a suitable agent for the intended purpose or such recognition should be anticipated in the near future.
- b. It should be compatible with construction materials in the areas where fires may occur and with materials used in the extinguishing systems. There should be, at most, minimal corrosion problems due to extinguishment, either from the neat agent or from likely decomposition products. This is particularly important for aircraft engines and for areas where contact with electronic components could occur.
- c. It should comply with the provisions of the Montreal Protocol. It must have a near-zero ozone depleting potential. Low Global Warming Potential (GWP) and atmospheric lifetime are desirable, but presently there are no generally accepted requirements. Nevertheless, GWP and atmospheric lifetimes were considered in these analyses.

4.2 ENGINE AND APU COMPARTMENT.

Title 14 Code of Federal Regulation (CFR) Part 25.1195 [107] identifies the requirements for fire suppression systems in aircraft power plants:

1. A fire suppression system is required if other means are not provided to control typical fires, as identified in the CFR.
2. The suppression system must be shown to be effective in quantity of agent, rate of discharge, and distribution by live test during actual or simulated flight conditions.
3. The suppression system must provide adequate, simultaneous protection throughout the compartment.

These requirements apply to all designated fire zones except for combustor, turbine, and tail sections of the turbine engine installations that contain lines or components carrying flammable fluids or gases. These areas are exempted because a fire originating in these sections can be controlled.

The fire threat addressed for these compartments is a Class B fire (aviation fuel, hydraulic fluid, lubricant). The compartments are normally ventilated, have complicated air flow pathways, possess excessively heated materials, and are approximately at ambient pressure. Considerations which may adversely impact the system design are the continual presence of ventilation air flow during and after an agent discharge, potential residual fuel after a shutdown, and the presence of heated surfaces.

Fires result when an engine failure provides simultaneous conditions permitting combustion. Typically, a flammable fluid release results from a mechanical failure. This fluid then comes in contact with an ignition source—possibly hot surfaces or gases associated with operating conditions at the time of failure, abnormal conditions posed by friction (heat or sparks), or electrical energy. Any fire that is detected by thermal sensors activates aural and visual fire warnings on the flight deck. The accepted practice to combat an engine compartment fire is to eliminate ignition and fuel sources and then discharge the fire suppression system. The process is achieved by shutting the engine down, closing local flammable liquid valves, turning off local electrical power, and then discharging the suppression system.

The fire suppression system is evaluated by an agent discharge test, which confirms the capability of the distribution system to provide the design agent concentration for the necessary time duration. The test requires an engine to be operating at critical conditions when the agent release occurs. Typically, 12 sampling probes from a gas analyzer, customarily a Statham or Halonizer type unit, are located in the compartment during this test. The device records the discharge event in the form of a gas concentration vs. time relationship. The record is reviewed for compliance with FAA-accepted criteria for certification. Advisory Circular 20-100 [108] provides a good summation for the aspects of a discharge test.

The earlier reports [1 and 2] proposed establishment of tests for the following two groups of agents. Note that these two groups cover a range of properties and, therefore, cover the range of testing procedures and apparatuses that should be established for halocarbon agents. Based, in part, on these recommendations and the information presented in the earlier reports, a task group consisting only of airframe manufacturer and airline representatives identified three halocarbon agents (HFC-125, HFC-227ea, and FIC-131I) as being particularly promising. Since HFC-125 was already being evaluated by the U.S. Department of Defense (DoD), it was proposed that the FAA evaluate HFC-227ea and FIC-131I. The FAA distributed a survey package to airlines and engine, APU, and airframe manufacturers to determine opinions on these two agents and on SPGGs as an alternative technology. Users preferred halocarbons, with SPGGs being considered only as a second choice [109]. Users also expressed significant concern regarding safety and human exposure to agents. Again, in September 1999, the FAA working group evaluated the status of current fire suppression agents [110]. The group issued a directive to evaluate CF_3I first, followed by HFC-125. Additional commentary describing other potential agents is included in the report.

At the time that this report was prepared, a Minimum Performance Standard (MPS) for aircraft engine nacelles was still being prepared. The MPS is currently in a working draft awaiting proof by testing.

4.2.1 HCFCs, HFCs, PFCs, and Blends.

These agents are similar in their performance and in their system characteristics. For this reason, they can be treated together when establishing a test protocol. These materials are typical PAAs.

Heptafluoropropane (HFC-227ea) and pentafluoroethane (HFC-125) are the agents of first choice within this group. Both were on the final list of agents being tested at Wright-Patterson AFB and both are recognized acceptable agents for Class B fires by technical and listing organizations, such as UL or equivalent. Both HFC-227ea and HFC-125 are acceptable under SNAP as a Halon 1301 substitutes [9]; however, under the present NFPA Standard 2001 [21], HFC-125 will be restricted to normally unoccupied areas for most fuels (not a problem in this application). It is also recommended that at least one blend be included in establishing test protocols since there may be differences between blends and pure materials in handling and/or performance.

HFC-125 was the final candidate from the DoD program. The program concluded with a design model for HFC-125 [111] that affords the designer the ability to calculate agent mass requirements for a particular nacelle or APU compartment based on parameters of ventilation air temperature and mass flow rate, anticipated fuel type, and compartment volume. This model is based on many points of fire extinguishment data produced in a test fixture. Guidance for the designer and limitations of the model are incorporated in the report.

A second source for HFC-125 design information can be found within the U.S. Navy. The Navy's F/A-18E/F underwent an evaluation with respect to potential fire suppression technologies for its aircraft engine nacelle. Ultimately, a quantity of HFC-125 considerably less than that predicted as necessary by the design equation derived from the earlier DoD program, successfully met the design challenge [112]. This effort is based on fire test results as produced in a complex test fixture representing the aircraft engine nacelle. The result represents a single point, but does offer another perspective on the performance for HFC-125 in the engine nacelle.

4.2.2 Trifluoromethyl Iodide (FIC-13I1) and FIC-13I1 Blends.

Testing at Wright-Patterson AFB has demonstrated that the chemically active agent trifluoromethyl iodide (FIC-13I1) is more effective in engine nacelle fire extinguishment than any other replacement halocarbon tested to date. A number of blends of CF_3I with other halocarbons have been reported as candidate extinguishing agents [113-115]. The material is acceptable under SNAP [11 and 12] in both streaming and total-flood applications with some use restrictions. The environmental characteristics are good, and the volume requirements and effectiveness are essentially identical to those of Halon 1301. A paper from NOAA (National Oceanic and Atmospheric Administration) states that

“...the extremely short lifetime of CF_3I greatly limits its transport to the stratosphere when released at the surface, especially at midlatitudes, and the total anthropogenic surface release of CF_3I is likely to be far less than that of natural iodocarbons such as CH_3I on a global basis. It is highly probable that the steady-state ozone depletion potential (ODP) of CF_3I for surface releases is less than 0.008 and more likely below 0.0001. Measured infrared absorption data are also combined with the lifetime to show that the 20-year global warming potential

(GWP) of this gas is likely to be very small, less than 5. Therefore this study suggests that neither the ODP nor the GWP of this gas represent significant obstacles to its use as a replacement for halons." [116]

It should be noted that the likely ODP is actually less than that determined for some of the hydrofluorocarbons (HFCs), which are given a nominal ODP of zero [117]. The cardiotoxicity of CF_3I is greater than that of other halocarbon candidates; however, the relatively low cardiac sensitization NOAEL and LOAEL values may be of little concern for engine nacelle and APU applications where potential for contact is extremely limited.

Note: Agent concentrations required for the engine and APU compartment may differ from the design concentrations as determined from heptane flame-extinguishing concentrations (table 8) because (a) fuel is shut off prior to the initiation of suppression, (b) compartments are ventilated, and (c) the fuel is different. Also, the discharge time influences agent quantity. The heptane flame-extinguishing concentrations (and design concentrations) presented in table 8 are intended to provide a basis of comparison. Required concentrations and their duration must be determined by testing. A concern has been expressed about the distribution of CF_3I in the protected compartment during low ambient temperature conditions if it is used as a drop-in agent in present systems [118]. This concern arises due to dispersion differences in CF_3I and Halon 1301 properties at low temperature and may require modifications of existing supply/distribution systems.

4.2.3 Gas Generators.

Inert solid propellant gas generators (SPGGs) have been tested in the U.S. Navy F-18 engine bay [119]; the results, however, were not promising. No SPGG tested provided adequate fire extinguishment [120]. It has been predicted that an SPGG used in engine bay fire protection will impose a take off gross weight (TOGW) penalty significantly lower than that expected for a typical halocarbon extinguishing system (HFC-125) [121]; however, the changes in insulation and distribution lines required to protect against the hot gases from an SPGG and the relatively large, bulky first-generation systems, now appear to make this unlikely. Studies indicate that factors other than oxygen starvation or cooling contribute to flame suppression by SPGGs in military aircraft engine bays [122]. One success story is the successful extinguishment of a real, hydraulic-fluid-fed mid-wing fire involving the rotor positioning unit (RPU) in a Navy V-22 aircraft [123].

Although work to date with aircraft engine bay fire protection using an SPGG technology has not been as promising as expected, it is far too early to rule out the use of this technology in engine nacelles.

4.3 HAND-HELD FIRE EXTINGUISHERS.

Federal Aviation Regulations mandate hand-held fire extinguishers be conveniently located in passenger compartments. The number of required extinguishers depends on the passenger capacity of the airplane [124]. The total number of extinguishers required are shown in table 17.

It is required that at least one of the extinguishers on an airplane with a passenger capacity greater than 31 and two on an airplane with a passenger capacity greater than 61 must contain Halon 1211 (bromochlorodifluoromethane) or equivalent as the extinguishing agent. The minimum performance standard defines the equivalency.

TABLE 17. HAND-HELD EXTINGUISHERS REQUIRED FOR
COMMERCIAL AIRCRAFT

Passenger Capacity	Number of Extinguishers
7 through 30	1
31 through 60	2
61 through 200	3
201 through 300	4
301 through 400	5
401 through 500	6
501 through 600	7
601 through 700	8

In addition, at least one hand-held fire extinguisher must be located in the pilot compartment, and at least one extinguisher must be available for use in each Class A^b or Class B cargo or baggage compartment and in each Class E cargo or baggage compartment that is accessible to crew members during flight.

A hand-held fire extinguisher for aviation use must meet the following requirements. These requirements are specified in detail in the Minimum Performances Standard (MPS) [125 and 126].

- a. Any hand-held fire extinguisher adopted for final use should be listed by a listing organization such as UL or equivalent, be of a specific rating, and be of a size and weight that a typical flight attendant can use. The smallest recommended hand-held extinguisher has a UL 5-B:C rating in accordance with the UL 711 Standard [127] or a BS 3A:34B rating in accordance with British standards [128]. This corresponds to 2.5 pounds for a Halon 1211 extinguisher. It is expected that this UL 5-B:C or BS 3A:34B fire-extinguishing ability along with a demonstrated ability to extinguish a hidden fire will be required for agents used in this application.
- b. The extinguisher must be able to extinguish fires in indirectly accessible spaces (hidden fires) as effectively as Halon 1211. It is desirable that the agent be sufficiently volatile to allow expansion and penetration into such spaces. Hand-held extinguishers are by nature streaming agents; however, Halon 1211 has the ability to also function as a flooding agent. To insure no loss of safety, replacement agents must maintain this ability. A hidden fire test has been developed to assess the firefighting performance of the hand-

^b To avoid confusion with fire types, the classification of cargo compartments is underlined in this report.

held extinguisher/agent combination in a flooding scenario. This test was developed by Kidde International-UK. The operating procedure has since been refined and standardized at the FAA William J. Hughes Technical Center, USA. The hidden fire test will be administered by Underwriters Laboratory. Extinguishers that are filled with acceptable agents (see "c" below) and pass the hidden fire test will receive FAA approval to replace Halon 1211 in aircraft cabins.

- c. The extinguisher must have an acceptable toxicity for use where people are present and must not cause unacceptable visual obscuration or passenger discomfort. In particular, the combined toxicity of the agent and fire products must not be unacceptable for use in an aircraft fire under in-flight conditions. The FAA has determined that the following agents are acceptable from a toxicity viewpoint for use in occupied aircraft cabins: Dupont FE-36, Great Lakes Chemical FM-200, POWSUS Envirogel, NAFG PIV, and American Pacific Halotron. The FAA aircraft seat fire toxicity test was conducted with each of these agents and the toxicity criterion applied to assess acceptability.

In the first report [1], the Task Group recommended establishment of tests for the following groups of agents. Note that these three groups of agents operate by different mechanisms and/or have large differences in physical properties. They cover the range of testing procedures and apparatuses that should be established. Dry chemical extinguishing agents are not listed due to (1) the potential for damage to electronic equipment, (2) the possibility of visual obscuration if the agent were to be discharged in the cockpit area, and (3) the clean up problem that results from their use. Restricting the use of dry chemicals to cabin areas does not prevent an extinguisher from inadvertently being carried to the cockpit and discharged in an emergency.

The Civil Aviation Authority (CAA) in the UK has sponsored research establishing a hidden fire test for onboard hand-held fire extinguishers [129]. A test fixture was developed that was comprised of arrays of four fires in two of five locations to establish those regions in which an extinguishing concentration was attained. A matrix of ten tests ensured that each fire location was adequately represented. Tests were carried out with several commercially available hand-held extinguishers. Results varied from 45- to 60-percent extinguishment depending on the quantity of halon contained in the extinguisher and the discharge rate (a faster discharge rate creates more turbulence, aiding mixing and dispersion). In addition, tests were carried out using under- and over-filled extinguishers to examine the sensitivity of the test method. With the exception of one hand-held extinguisher, all results could be correlated to the mass of agent and the flow rate used.

The CAA project carried out limited testing with six halon replacements: HFC-227ea, HFC-125, FC-3-1-10, FC-5-1-14, HFC-236fa, and FIC-131I, using apparatus designed to give a constant discharge time (10 ± 1 seconds). The results obtained appeared to be similar to Halon 1211 (50 ± 5 percent extinguishment), provided the quantity of agent is scaled according to its *n*-heptane cup burner concentration. The two exceptions were agents whose volatility is markedly different from that of Halon 1211 (boiling point: -4°C (24.8°F), HFC-125 (boiling point: -49°C (-56.2°F), 65-percent extinguishment), and FE-5-1-14 (boiling point: 58°C (136.4°F), 35-percent extinguishment). The testing indicated that use of the physically acting candidate agents (all

except FIC-13I1) would give a weight penalty of 1.4 to 2.6 and a volume penalty of 1.9 to 2.9 compared to Halon 1211.

4.3.1 Halocarbons and Halocarbon Blends.

Of all of the halocarbon agents, FICs and, possibly to a lesser extent, HFCs are likely to have the lowest restrictions imposed owing to environmental impacts. Nevertheless, even HFCs could face additional regulatory restrictions. FIC-13I1 (like some of the other halocarbons) will also face some restrictions based on toxicity. Under SNAP, this agent is not permitted as a total-flood agent in a normally occupied area.

HCFCs have a nonzero ODP and currently face an eventual regulated production phaseout. The phaseout dates in the United States depend on the material (table 6); however, all HCFCs now considered for streaming have the same phaseout schedule. When used in nonresidential applications, portable fire extinguishers containing HCFCs are exempted by the U.S. EPA from bans on HCFC-pressurized dispensers [130]. At least one HCFC-based agent should be considered in this application because of their gaseous consistencies and their demonstrated abilities on Class A, B, and C fires.

PFCs are approved by the U.S. EPA [9] (FC-5-1-14 for streaming, FC-218 and FC-4-1-10 for total flooding) for nonresidential use where other alternatives are not technically feasible due to performance or safety requirements: (1) due to physical or chemical properties of the agent, or (2) where human exposure to the extinguishing agent may result in failure to meet applicable use conditions. The principal environmental characteristic of concern for these materials are their extremely high GWPs and long atmospheric lifetimes. Nevertheless, PFCs should be considered in this application because of their extremely low toxicity.

Some concern has been expressed about preliminary mutagenicity assays indicating that CF_3I might be a carcinogen. Certainly this question may need to be resolved; however, some other halon replacement candidates or components also exhibit positive results in at least one genetic toxicity screening test. In addition, there is some concern that iodine emissions from CF_3I could cause a problem. No data have yet been collected showing that iodine emissions are any worse with CF_3I than bromine emissions are with Halon 1211. Nevertheless, the potential for toxic breakdown products must be fully evaluated.

It is difficult to rank the various halocarbon agents against one another since any ranking requires that dissimilar criteria be compared (e.g., toxicity versus effectiveness), nevertheless, table 18 gives ratings for two criteria (Halon 1211 is also listed for comparison). Here "1" denotes the highest rating. Note that this is qualitative and, undoubtedly, different groups could arrive at different ratings. It is impossible to reliably evaluate the effectiveness of a streaming agent from only cup burner extinguishment concentrations, particularly when the cup burner measures only Class B effectiveness. Nevertheless, the cup burner values, where known, have been included. These can be used as deemed appropriate. The ability of an agent to suppress a fire in a streaming application depends as much on the physical properties and delivery hardware as on the inherent flame-suppressing ability. (Note that this is definitely not true for total-flood

applications. The cup burner has proven to be highly reliable for predicting the effectiveness of total-flood agents for Class B fires, at least for those containing a single component.)

TABLE 18. RATING MATRIX FOR CANDIDATE HALOCARBONS FOR HAND-HELD

Agent	Cup Burner Extinguishment Concentration, %	Known or Potential Environmental Regulatory Restrictions ^a	Toxicity Based on Cardiac Sensitization NOAEL
Halon 1211	2.22 ^b	5	3
HCFC-123	7.5 ^c	3	3
HCFC-124	6.6 ^g	3	3
HCFC Blend B HCFC-123	6-7 ^e	3	3
HCFC Blend C HCFC-123 HCFC-124 HFC-134a	f	3	3
HCFC Blend D HCFC-123	f	3	3
HCFC Blend E	f	f	f
HFC-227ea	6.5 ^g	2	2
HFC-236fa	6.3 ^g	2	2
FC-5-1-14	4.4 ^d	4	1
FIC-1311	3.2 ^g	1	5

^a Only includes regulatory restrictions based on possible environmental impact. Does not include restrictions due to toxicity.

^b Reference 131

^c Reference 132.

^d Reference 9.

^e Estimated [133]. Testing indicates that HCFC Blend B has an equivalency rating of 1.5 pounds to 1 pound of Halon 1211 in airport fire protection streaming applications [134].

^f Data have not been published.

^g Reference 21.

The agent CF₃I is the agent least likely to face serious regulatory restrictions based on environmental impacts and has been given an environmental rating of 1. HFCs were given an environmental rating of 2 due to global warming concerns. Halon 1211, which is already restricted, has been assigned an environmental rating of 5 due to its high ODP. Toxicity indices were assigned based on the NOAEL values of the primary components. Note, however, that acceptability for total-flood use in normally occupied areas is not a criteria for use of an agent for streaming. For a NOAEL < 0.5, the toxicity rating = 5; NOAEL = 0.5 to <1.0, rating = 4; NOAEL = 1.0 to <5.0, rating = 3; NOAEL = 5.0 to <20.0, rating = 2; and NOAEL = 20.0 or above, rating = 1. It should be noted that, for streaming applications, most and possibly all of

these halon replacement agents could be used in a normally occupied area. Extensive full-scale testing of both HCFC Blend B and FC-5-1-14 for flight line fire protection has been conducted by both the FAA and the U.S. Air Force. The U.S. Air Force has also conducted significant field testing on several other agents listed in table 18.

4.3.2 Carbon Dioxide.

There has been a large amount of experience with hand-held carbon dioxide fire extinguishers. They are known to be safe to use in a streaming application where people are present, and the carbon dioxide should be able to reach into indirectly accessible areas. A major problem exists in the lack of a Class A rating for hand helds in sizes from 5 pounds (5-B:C rating) to 100 pounds (20-B:C). If testing shows that carbon dioxide extinguishers cannot extinguish Class A fires of the type likely to be found in cabin fire scenarios, this agent would have to be eliminated from consideration.

4.3.3 Combination Agents and Foams.

These agents include Surfactant Blend A, Loaded Stream, and Gelled Halocarbon/Dry Chemical Suspension. Though these are listed together, their properties are sufficiently different, therefore, major differences in test procedures will probably be required. In the absence of test results, it is impossible to rank the fire extinguishment effectiveness in hand helds for aircraft use. They should all prove very effective for Class A fires; however, these agents may very well lack the ability to penetrate in indirectly accessible spaces. A study of hand-held fire extinguishers by FMRC states that "around object capability" for Halon 1301 is good, dry chemical is poor, and water is poor [135]. Most, and possibly all, combination agents may also have problems with penetration and obstacles. Moreover, there could be some compatibility problems with electrical equipment and, possibly, structural materials with some of the combination agents. Both the Surfactant Blend A and the Gelled Halocarbon/Dry Chemical Suspension series of agents are EPA approved.

4.4 CARGO COMPARTMENT.

The recent ruling eliminating Class D as an option for fire safety certification for cargo compartments in certain transport category aircraft will increase the number of compartments requiring fire suppression systems [136]. Such compartments must now meet the standards of Class C and/or Class E compartments. Most Class C compartments are larger than 1000 ft³; many are larger than 2000 ft³.

According to the report of Task Group 4 [137], the likely fire by an aircraft-supplied ignition source is a surface fire and will most likely be fueled by Class A material. In some instances, the Class A material may be contaminated by small quantities of Class B material. Human- and cargo-supplied ignition sources can cause a variety of fires (deep seated, flaming, explosive, metallic, fires with their own oxidizer, chemical, etc.). These fires are not easily characterized, but the task group defined, as specified in the Cargo Compartment Minimum Performance Standard, four different fire test scenarios in order to address the variety of fires.

A cargo compartment fire suppression system must meet the following fire test requirements. (See table 19 to obtain maximum allowable compartment temperatures.)

- a. The system must suppress a Class A deep-seated fire (bulk-loaded cargo) for at least 30 minutes.
- b. The system must suppress a Class A fire inside a cargo container for at least 30 minutes.
- c. The system must extinguish a Class B fire (Jet-A fuel) within 5 minutes.
- d. The system must prevent, either by fire control or inerting the compartment, the explosion of an explosive hydrocarbon mixture.

The cargo compartments are normally pressurized with a minimum normal pressure corresponding to an altitude of 8,000 feet. In flight, the temperatures are maintained above freezing by several means, including ventilation. Fire in the cargo compartments is detected by smoke and ionization aerosol detectors or thermal sensors. The fire detection system is required to detect and provide visual indication of the fire to the flight crew within 1 minute after the start of a fire. Also, the system must be capable of detecting a fire at a temperature significantly below that at which the structural integrity of the airplane is substantially decreased (FAR 25.858 [138]). Fire detection systems are certified using an FAA-approved fire simulator.

Systems that provide a warning within 1 minute from the start of smoke generation are considered to be in compliance with FAR 25.858 [138]. The present practice is to control ventilation and drafts within the compartment prior to the activation of the suppression system. However, there is a small infiltration into the compartment through the compartment walls (typically fiberglass liner) and leakage out of the compartment through door seals. The general practice is to divert to the nearest field on detection of a fire. On long-range (across the ocean) aircraft, suppression is required for up to the maximum diversion time which could be in excess of 200 minutes.

The agent or system for cargo compartments must meet the following requirements in addition to the essential requirements identified earlier.

The agent/system for cargo compartments must also meet the requirements of FAR 25.851, Part B [139] and FAR 25.1309 [140].

- a. The agent/system must be suitable for fires likely to occur. These include Class A and B fires and hazardous materials.
- b. The agent/system must be able to provide fire suppression over a period of up to the maximum diversion time, which could be in excess of 200 minutes, depending on the aircraft type and route structure.

It is desirable for the agent to have the following attributes.

- a. Because cargo compartments can be used for transportation of animals, it is desirable that the agent have a low toxicity and that it not be an asphyxiant at the concentrations required for extinguishment. In addition, no agent can be allowed that could leak into occupied compartments in toxic concentrations. Federal regulations require that "There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by crew or passenger." Airframe manufacturers meet this by design. Typical cargo compartments contain a fiberglass liner, which is tested with a smoke generator for leakage and with burners for flame penetration. Escape of smoke or extinguishing agent in hazardous quantities from cargo compartments of properly maintained aircraft is unlikely.
- b. The agent should not impose additional (in addition to system recharge and check-out) departure delay following a false discharge.

The FAA has distributed a survey package to airlines and airframe manufacturers to determine opinions on agents and technologies proposed for cargo compartments in the earlier reports [1 and 2]. The response was poor. A majority (60 percent) of those responding preferred halocarbons, with a small, but significant, number believing that water and particulate aerosols are best [141]. Respondents were unanimous that the high-expansion foams are not appropriate for use in cargo compartments. Due to this negative response and technical considerations, high-expansion foams have been removed from the list of agents proposed in the past by the Task Group on Halon Options for cargo compartments. The remaining agents—water and water-based agents, halocarbons and halocarbon blends, and particulate aerosols—are still recommended for the establishment of test protocols.

The Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems was published September 2000 [142]. This document provides the extinguishing/suppressing performance of Halon 1301 (when subjected to the four fire scenarios mentioned earlier) and the standard test protocols. Currently, the aerosol explosion protocol section, in this standard, is being modified by the FAA William J. Hughes Technical Center in order to allow the inclusion of a nongaseous system such as water spray.

FAA test data are now available on Halon 1301, HFC-125, HFC-227ea, PGA, and water mist. The MPS requirements are shown in table 19 for a 2000-ft³ cargo compartment.

TABLE 19. ACCEPTANCE CRITERIA FOR A 2000-cubic foot CARGO BAY

Fire Scenario	Maximum Temperature °F (°C)	Maximum Pressure psi (kPa)	Maximum Temperature-Time Area °F-min (°C-min)	Comments
Bulk Load	730 (387.8)	^a	11,900 (6593)	Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 30 minutes starting with suppression system activation.
Containerized Load	670 (354.4)	^a	15,400 (8538)	Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 30 minutes starting with suppression system activation.
Surface Fire	1250 (676.7)	^a	3,270 (1799)	Temperature limit starting 30 seconds after suppression system activation. Temp.-Time area for 5 minutes starting with suppression system activation.
Aerosol Can	^a	0	^a	There shall be no explosion

^a Not applicable.

4.4.1 Water and Water-Based Agents.

Water meets almost all of the above requirements. A water system needs to be challenged against the MPS aerosol explosion test to determine its explosion prevention capabilities. Water is the most common fire-extinguishing agent for ordinary combustibles. The efficiency of the agent depends on the application method (sprinkler, mist, total flood, zoned application, etc.). Several investigators have determined it to be as effective as Halon 1301 for identical fire threats. It can be used in misting or sprinkler applications. In the present application, it is recommended that testing of misting systems be performed; however, sprinkler systems could be considered. Both sprinklers and misting systems could use a zoned application. It is possible to use surfactant/water or dry chemical/water blends; however, in the absence of test results to the contrary, it is difficult to determine what benefit would ensue from the use of such mixtures. Moreover, such mixtures could cause an increase in cleanup efforts.

The FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey, has carried out a mist system testing program for the FAA TC-10 cargo test compartment. The objective was to design and install a water mist system that would prevent a fire in a luggage container from spreading to an adjacent luggage container and maintain temperatures within the space below 350°C for 90 minutes. The program has shown that one misting system can pass

both the loaded luggage container and bulk-loading fire tests for the TC-10 cargo test compartment using 30 gallons of water [143]. These results are encouraging and suggest that an area-coverage water mist system may impose a lower takeoff gross weight (TOGW) penalty for large cargo compartments. Another advantage may be lower sensitivity (compared to gaseous agents) to compartment leakage.

It has been suggested that water-based fire suppression systems may be recharged from the portable water system if the initial capacity fails to adequately suppress a fire. It has also been proposed that it may be possible to recycle water using runoff from discharge to reduce the amount of water needed to provide protection. These proposals would require significant engineering to incorporate and may not be practical. Water-based systems may provide an acceptable environment for animals in the event of a false discharge. In addition, water-based systems may not depend on the integrity of the compartment liner for effective performance. Some concerns have been expressed about the possibility of stored water freezing; however, design solutions are available to prevent such occurrences.

4.4.2 Halocarbons and Halocarbon Blends.

Table 20 gives a rating for various criteria for halocarbons in cargo compartments. Here "1" denotes the highest rating. Arbitrarily, ratings for design concentrations have been assigned as

- 5 percent and below: 1
- 5 to 8 percent: 2
- 8 to 11 percent: 3
- above 11 percent: 4

Ratings for storage volume and weight equivalents are given ratings as follows:

- 1.0 or less: 1
- 1.0 to 1.5: 2
- 1.5 to 2.0: 3
- above 2.0: 4

Note that these effectiveness ratings were derived from data for a Class B fire with *n*-heptane fuel. They may not indicate performance for a deep-seated Class A fire, which is the probable fire in cargo compartments. Agents with NOAEL values of 30 percent or above are rated as 1 for toxicity. Agents with NOAEL values less than 30 percent but which are acceptable (or likely to be acceptable) for total flood in normally occupied areas under NFPA Standard 2001 [21] are given a rating of 2. HFC-125, whose NOAEL value is only slightly less than that which would allow total-flood use in normally occupied areas, is given a rating of 3. HCFC-124 with a NOAEL of 1.0 and FIC-131I with a NOAEL of 0.2 are rated as 4 and 5, respectively. Note, however, that cargo compartments are not considered to be normally occupied areas. Due to its high-vapor pressure, the delivery characteristics and system requirements for HFC-23 may differ significantly from those for most other halocarbons.

TABLE 20. RATING MATRIX FOR CANDIDATE HALOCARBONS FOR CARGO COMPARTMENT

Agent	Class B Fire Design Conc., %	Class B Fire Weight Equivalent	Class B Fire Storage Volume Equivalent	Known or Potential Regulatory Restrictions ^a	Cardiac Sensitization NOAEL
HCFC-124	3	3	3	3	4
HCFC Blend A	3	2	2	3	2
HFC-23	4	3	4	2	1
HFC-125	3	3	4	2	3
HFC-227ea	2	3	3	2	2
HFC-236fa	2	2	2	2	2
FC-218	3 ^b	4 ^b	4	3	1
FC-3-1-10	2	3	3	3	1
FIC-131I	1	1	1	1	5

^a Only includes regulatory restrictions based on environmental impact. Does not include restrictions due to toxicity.

^b The storage volume and weight equivalents used in determining ratings for this agent, which does not appear now in the NFPA Standard, were calculated from the design concentration, molecular weight, and the liquid density. Ratings for the other agents were determined from equivalents calculated using weight requirements and fill densities as reported in the NFPA 2001 Standard [21]. See table 8 and 9.

There has been some work indicating that misting (and, perhaps, standard discharge) of higher molecular weight (lower-vapor pressure) halocarbons can provide total-flood-like protection of enclosed areas [144]. At present, no manufacturer offers such a system, and the technology must still be considered unproven. However, the possibility that one or more new, lower-vapor pressure compounds will be proposed for total-flood protection must be kept in mind.

Class A fires develop slowly. It is feasible to detect a fire in a cargo compartment within a zone and suppress it by a zoned fire suppression system. In the past, total-flood systems have been used, but the federal regulations do not mandate a total-flood system. The halocarbon agents fall in two categories: liquid agents, which could be applied in a zoned application, and gaseous agents for total-flood applications. It is recommended that test protocols for both types of agents be developed.

4.4.3 Particulate Aerosols.

Some preliminary testing has been performed by the FAA on type S.F.E. formulation "D" particulate aerosols using modular units of 4 kilograms each. The scope of the test was to evaluate the S.F.E. aerosol performance on deep-seated Class A fires, specifically shredded papers. The FAA requirements were to extinguish the fire and inert the protected volume for 30 minutes. The S.F.E. particulate aerosol formulation "D" was tested at an application

concentration of 60-100 gr/m³. The agent partially suppressed a Class A fire in a 2357-ft³ compartment and inerted the volume for approximately 17 minutes [83].

These preliminary results and consideration of the possible weight/volume cost benefits of the particulate aerosols technology, render its application to aircraft fire protection as potentially viable, and the technology should be further evaluated.

4.5 LAVATORY TRASH RECEPTACLE.

Lavatories are located in the pressurized aircraft cabin with environmental conditions similar to the conditions in other occupied areas. The likely fire threat in the lavatory trash receptacle would involve Class A materials (paper and paper products), with the typical ignition source being burning material discarded into the container, such as a lit cigarette. The trash containers are designed to contain the likely fire. No fire detection system is provided in the container. Rulemaking was implemented on April 29, 1987, that required each lavatory trash container be equipped with a built-in automatic fire extinguisher that discharges automatically into the container upon the occurrence of a fire. In order to accomplish this, the extinguisher bottle incorporates a eutectic device at the end of a tube directed into the container. In the event of a fire, the heat generated will melt the eutectic tip, releasing the agent directly into the receptacle. Currently, all aircraft lavatory disposal receptacle fire extinguishers use Halon 1301 as the fire-extinguishing agent. A relatively small amount of agent (100 grams of 1301) is effective in extinguishing this type of fire. For this reason, suitable gaseous replacement agents such as HFC-227ea and HFC-125 can be used in this application, as the additional amount of agent required to extinguish the fire is negligible.

The agent for trash containers must meet the following requirements in addition to the essential requirements identified earlier in Section 4.1, Requirements [145].

- a. The agent must extinguish a Class A (paper towel) fire as defined in the Minimum Performance Standard (MPS) [145].
- b. The agent must have a toxicity such that, if the same quantity of agent used for the trash container is released into the entire lavatory, the NOAEL is not exceeded.

A survey of 24 airlines showed that 66 percent preferred halocarbons or halocarbon blends for use in aircraft lavatory trash receptacles [146]. The reasons given for this preference were reduced weight, minimum impact on current installation, and effectiveness. Sixteen percent preferred water, giving as reasons, low environmental impact and reduced maintenance. Weight and effectiveness concerns were mentioned as potential drawbacks for water. The IHRWG, Task Group 7, and the FAA have established a Minimum Performance Standard for lavatory trash receptacles. The following agent types are most likely to have utility in lavatory trash receptacle applications: HFC-125, HFC-227ea, HFC-236fa, and Envirolgel.

4.5.1 Water-Based and Combination Agents.

Water, water/surfactant (e.g., Surfactant Blend A), Dry Chemical/Water Mixtures, and combination agents meet all the above requirements. Water is the most common fire-

extinguishing agent for paper products. The efficiency of the agent depends on the application method (sprinkler, mist). Loaded stream or surfactant blends could improve surface wetting of Class A materials. These are all likely to be more effective on Class A materials than halocarbons. Pacific Scientific is commercializing a lavatory fire extinguisher containing Envirolgel.

4.5.2 Halocarbons and Halocarbon Blends.

Most halocarbons would provide acceptable extinguishing ability in this application. Moreover, recent work with HFC-227ea suggests that some halocarbons might allow retrofit into existing systems [147]. However, to achieve the required low-temperature performance (5°F), some halocarbons will need to be pressurized with nitrogen. Since the system may be as important as the agent, it is difficult or impossible to rank agents for this application. This will be primarily a system test.

4.6 SUMMARY.

Fire-extinguishing agent technology is extremely dynamic. A number of new agents and technologies are being evaluated in the laboratories across the nation. The recommendations above are based on the present state of the technology, EPA approvals, and listing by technical organizations. These recommendations are intended to guide the FAA in the development of the test protocols. It must be recognized that a test protocol developed for a class (liquid, gaseous, solid) of agents may, with minor modifications, be used to test all agents belonging to the class.

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APPENDIX A—COMPANIES AND MANUFACTURERS

HALOCARBON AGENT PRODUCERS

Ajay North America
Contact: Newhouse International Inc
CF₃I (Triiodide)

American Pacific Corporation
Halotron Division
3770 Howard Hughes Parkway, Suite 300
Las Vegas, Nevada 89109
USA

Telephone: 1-702-735-2200
Fax: 1-702-735-4876
Email: halotron @apfc.com
Web: www.halotron-inc.com/

HCFC Blend B (Halotron 1)

DuPont Fluoroproducts
Chestnut Run Plaza 702-2320E
P.O. Box 80702
Wilmington, Delaware 19880-0702
USA

Telephone: 1-302-999-4459
Fax: 1-302-999-2816
Email: info@dupont.com
Web: http://www.dupont.com/fire

HFC-23 (FE-13);
HFC-125 (FE-25);
HFC-236fa (FE-36);
HCFC-123 (FE-232);
HCFC-124 (FE-241)

Great Lakes Chemical Corporation
P.O. Box 2200
West Lafayette, Indiana 47906
USA
Fax: 1-765-463-2849
Email: fluorwhq@glcc.com
Web: www.fm-200.com
http://www.greatlakeschem.com/index.html
HFC-227ea (FM-200)

Newhouse International Inc.
Sales of CF₃I
6855 East Swarthmore
Anaheim, CA 92807
USA
Telephone: 1-714-685-9920
Fax: 1-714-685-9921
Email: cf3i@concentric.net
Web: www.cf3i.com
CF₃I (Triiodide)

North American Fire Guardian Technology Inc.
Unit 300, 625 West Kent Avenue North
Vancouver, BC V6P 6T7
CANADA

Telephone: 1-604-323-0090
Fax: 1-604-323-0051
Email: nafgt@ultranet.ca
Web: http://www.nafgt.com

HCFC Blend A (NAF S-III);
HCFC Blend C (NAF P-III);
HCFC Blend D (Blitz);
HCFC Blend E
(NAF P-IV)

3M Product Information Center
3M Center, Building 304-1-01
St. Paul, Minnesota 55144-1000
USA

Telephone: 1-651-737-6501
Fax: 1-651-737-7117
Email: innovation@mmm.com
Web: http://www.3M.com

C6F14 (CEA-614);
C4F10 (CEA-410);
C3F8 (CEA-308)

WATER MISTING SYSTEMS

Baumac International
1500 Crafton Avenue
Mentone, California 92359
USA
Telephone: 1-909-794-7631
Fax: 1-909-794-5795
Email: baumac@micromist.com
Web: <http://www.micromist.com>

Chemetron Fire Systems
4801 Southwick Drive
Matteson, Illinois 60443
USA
Telephone: 1-708-747-1503
Fax: 1-708-747-2847
Email: info@chemetron.com
Web: <http://www.chemetron.com/>

Fike Corporation
704 South 10th Street
P.O. Box 61013
Blue Springs, MO 64013
USA
Telephone: 1-816-229-3405
Fax: 1-816-229-4615
Email: fikecorp@fike.com
Web: <http://www.fike.com>

FOGTEC Fire Protection
Schanzenstraße 35
D-51063 Köln
GERMANY
Telephone: 49-221-96-22-3-0
Fax: 49-221-96-22-3-30
Email: fogtec@aol.com
Web: <http://www.fogtec.com>

GEC-Marconi Avionics Ltd.
Airport Works
Rochester, Kent ME1 2XX
UK
Telephone: 44-1634-844400
Fax: 44-1634-827332
Web: <http://www.gec-marconi.com/avionics/>

Ginge-Kerr Denmark A/S
111 Stamholmen
DK-2650 Hvidovre
DENMARK
Telephone: 45-36-77-11-31
Fax: 45-36-77-22-31
Email: ginge@ginge-kerr.dk
Web: www.kidde-int.com

Grinnell Fire Protection Systems Company
835 Sharon Drive
Westlake, Ohio 44145-1584
USA
Telephone: 1-440-899-5445
Fax: 1-440-871-2301
Web: <http://www.grinnellfire.com/>

GW Sprinkler
Glamsbjerg
DENMARK
Telephone: 45-647-22055
Fax: 45-6472-2255

International Aero, Inc.
11817 Westar Lane
Burlington, WA. 98233
USA
Telephone: 1-360-757-2376
Fax: 1-360-757-4841
Email: jbrooks@pyrogen.com
Web: <http://www.intl-aero.com>

Kidde-Deugra Brandschutzsysteme GmbH
Halskestrasse 30
D-40880 Ratingen
GERMANY
Telephone: 49-2102-405-149
Fax: 49-2102-405-151

Kidde International
Mathisen Way, Colnbrook
Slough, Berkshire, SL3 0HB
UK
Telephone: 44-1753-683245
Fax: 44-1753-689309
Email: sales.information@kidde-hq.com
Web: <http://www.kidde.co.uk/>

Marioff Oy
Hakamäenkuja 4
FIN 01511 Vantaa
FINLAND
Telephone: 358-9-8708-51
Fax: 358-9-8708-5399
Email: marioff@marioff.fi
Web: <http://www.hi-fog.com/>

Marioff Oy
3600 Commerce Drive
Suite 614
Baltimore, MD 21227
USA
Telephone: 1-410-737-6600
Fax: 1-410-737-6489
Web: <http://www.hi-fog.com/>

Phirex Australia
78 Roberts Street
Osborne Park 6017, Western Australia
AUSTRALIA
Telephone: 61-8-94443244
Fax: 61-8-94443255
Email: phirex@ois.com.au

Securiplex Inc.
549 Meloche Avenue
Dorval, Quebec H9P-2W2
CANADA
Telephone: 1-514-633-1000
Fax: 1-514-633-8338
Email: info@securiplex.com
Web: <http://www.securiplex.com/>

Semco Maritime A/S
Svendborgvej 226
5260S Odense
DENMARK
Telephone: 45-65-68-33-00
Fax: 45-65-95-75-29
Email: sales@maritime.semco.dk
Web: <http://www.maritime.semco.dk/>

Spraying Systems Company
P.O. Box 7900
Wheaton, Illinois 60189-7900
USA
Telephone: 1-630-665-5000
Fax: 1-630-260-0842
Email: info@spray.com
Web: <http://www.spray.com/index.htm>

Summit Environmental Corp.
414 E. Loop 281, Suite 7
Longview, Texas 75695
USA
Telephone: 1-903-758-0551
1-800-522-7841
Fax: 1-903-758-1903
Email: seci@eamerica.net

Total Walther
Feuerschutz und Sicherheit
Waltherstraße 51
D-51069 Köln
GERMANY
Telephone: 49-221-6785-427
Fax: 49-221-6785-207
Web: <http://www.totalwalther.com>

Yates Fire Protection
P.O. Box 9206
Hampton, VA 23670
USA
Telephone: 1-757-827-8696
Fax: 1-757-827-8697

Ultra Fog AB
Rödjansväg 7
SE-44934 Nödinge
SWEDEN
Telephone: 46-303-97375
Fax: 46-303-97376
Email: sprinklersystem@ultrafog.com
Web: <http://www.ultrafog.com>

PARTICULATE AEROSOLS

ADI Technologies, Inc.
1487 Chain Bridge Road, Suite 204
McLean, VA 22101
USA
Telephone: 1-703-734-9626
Fax: 1-703-448-8591
Email: adit22101@aol.com
Powdered Aerosol A (SFE)

Ansul Incorporated
One Stanton Street
Marinette, WI 54143, USA
USA
Telephone: 1-715-735-7411
Fax: 1-715-732-3478
Web: <http://www.ansul.com>
MICRO-K

Dynamit Nobel GmbH
Explosivstoff-und Systemtechnik
Defense and Industrial Products Division
Postfach 1261
53839 Troisdorf
GERMANY
Telephone: 49-2242-891280
Fax: 49-2241-89-16-69
Email: Michael.Hoerig@danamit-nobel.com
Powdered Aerosol C (Dynameco)

FireCombat Inc.
2650 Industrial Parkway
P.O. Box 407
Marinette, Wisconsin 54143-0407
USA
Telephone: 1-715-735-9058
Fax: 1-715-735-7223
Email: firecom@mail.mnm.earthreach.com
Aero-K

Kidde-Deugra Brandschutzsysteme GmbH
Halskestrasse 30
D-40880 Ratingen
GERMANY
Telephone: 49-2102-405-149
Fax: 49-2102-405-151
KD-A 96

International Aero Inc.
11817 Westar Lane
Burlington, Washington 98233-3621
USA
Telephone: 1-360-757-2376
Fax: 1-360-757-4841
Email: engr@intl-aero.com
Web: <http://www.intl-aero.com>
Pyrogen
Firepak

AES International Pty Ltd.
P.O. Box 694
Hurstville, NSW 2220
AUSTRALIA
Telephone: 61-2-9586-3200
Fax: 61-2-9586-3211
Web: www.pyrogen.com
Powdered Aerosol (PyroGen)

Spectrex Inc.
Peckman Industrial Park
218 Little Falls Rd.
Cedar Grove, New Jersey 07009
USA
Telephone: 1-973-239-8398
Fax: 1-973-239-7614
Email: spectrex@spectrex-inc.com
MICRO-K

INERT GASES

Ansul Fire Protection
One Stanton Street
Marinette, Wisconsin 54143
USA
Telephone: 1-715-735-7411
Fax: 1-715-732-3479
Web: <http://www.ansul.com>
IG-541 (Inergen)

Fire Eater A/S
Skovlytoften 14
DK-2840 Holte
DENMARK
Telephone: 45-40-50-74-63
Fax: 45-70-23-27-69
Web: <http://www.fire-eater.dk>

Ginge-Kerr Denmark A/S
Stamholmen 111
DK-2650 Hvidovre
DENMARK
Telephone: 45-36-77-11-31
Fax: 45-36-77-22-31
Email: Ginge@Ginge-Kerr.dk
Web: www.kidde-int.com
IG-55 (Argonite)

Koatsu Company, Ltd.
310, Kitahonmachi 1-chome
Itami-shi, Hyogo-ken 664-0836
JAPAN
Telephone: 81-0727-82-8561
Fax: 81-0727-82-8211
Email: info@koatsu.co.jp
Web: <http://www.koatsu.co.jp/05-01.htm>
IG-100 (NN100)

Minimax GmbH
Technisches Büro
Industriestraße 10/12
D-23843 Bad Oldesloe
GERMANY
Telephone: 49-4531-803-443
Fax: 49-4531-803-500
Web: www.minimax.de
IG-01 (Argotec)

Nohmi Bosai Ltd.
7-3, Kudan-Minami
4-Chome, Chiyoda-ku
Tokyo 102-8277
JAPAN
Telephone: 81-03-3265-0211
Fax: 81-03-3265-9228
Email: kouhou@nohmi.co.jp
Web: www.nohmi.co.jp
IG-100 (NN100)

GAS GENERATORS

Atlantic Research Corporation
5945 Wellington Road
Gainesville, Virginia 22065
USA
Telephone: 1-703-754-5231
Fax: 1-703-754-5605

General Dynamics
(formerly Primex Aerospace Company)
P.O. Box 97009
Redmond, Washington 98073-9709
USA
Telephone: 1-425-885-5000
Fax: 1-425-882-5744
Email: phw@red.gd-ots.com
Web: <http://www.primexfiresystems.com>
Inert Gas/Powdered Aerosol Blend (FS 0140)

Walter Kidde Aerospace, Inc.
4200 Airport Drive N.W.
Wilson, NC 27893-4717
USA
Telephone: 1-252-237-3787
Fax: 1-252-237-4717
Web: <http://www.kidde.com/commsist.htm>

COMBINATION AND NEW FOAM AGENTS

Cease Fire by Dis-Cover, Inc.
10355 Capital Avenue
Oak Park, Michigan 48237
USA
Telephone: 1-248-398-3660
Fax: 1-248-398-0081
Email: gfflood@ceasefire.com

Firefox Industries
P.O. Box 128
Murrysville, Pennsylvania 15668
USA
Telephone: 1-800-930-3366
Fax: 1-724-733-3823
Email: info@firefoxind.com
Web: <http://firefoxind.com>
FOAM A

FireFreeze Worldwide, Inc.
270 Route 46
East Rockaway, New Jersey 07866
USA
Telephone: 1-973-627-0722
Fax: 1-973-627-2982
Email: info@firefreeze.com
Web: <http://www.firefreeze.com/>
[Surfactant Blend] A (ColdFire)

Powsus Inc.
3120 N. A1A #1403
Fort Pierce, Florida 34949
USA
Telephone: 1-561-460-8729
Fax: 1-561-460-8730
Email: 753-0094@mcimail.com
Gelled Halocarbon/Dry Chemical Suspension (PGA)

Summit Environmental Corporation, Inc.
414 East Loop 281, Suite 7
Longview, Texas 75605
USA
Telephone: 1-800-522-7841
Fax: 1-903-758-1903
Email: seci@iamerica.net
Web: www.summitenvironmental.com
[Surfactant Blend] A (ColdFire 302/ FlameOut)

OTHER MANUFACTURERS CITED IN THIS REPORT

Pacific Scientific
HTL/Kin-Tech Division
1800 Highland Avenue
Duarte, California 91010
USA
Telephone: 1-626-359-7013
Fax: 1-626-359-7013